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Economic Effects of Global Warming: The Impact on the Life Cycle of Salmon Lice, With Knock-on Effects on Aquaculture and Angling Tourism

By Vegard Valberg and Jacky Lee

Abstract

Salmon lice, *Lepeophtheirus salmonis*, is a parasitic copepod endemic to Atlantic salmon. In recent year salmon aquaculture has created large breeding grounds for this parasite, as well as acting as a vector for infection on wild salmon. This has caused serious problems for both salmon aquaculture and angling tourism. In this thesis we examine how global climate change will affect the salmon lice problem, with emphasis on the economic impact.

In our thesis we use temperature projections combined with models of salmon lice infection pressure for quantitative data on the effects of climate change on the salmon lice problem. We tested several scenarios and variations to see if any of them had a disproportionate impact. This was followed by a qualitative analysis of the wider economic impact.

Our study shows there will indeed be increased infection pressure from salmon lice. This will negatively affect salmon aquaculture, as well as both entrepreneurs and local communities that depend on salmon angling tourism. Knock-on effects may even include lower property prices on salmon rivers. We further argue this is could cause stricter regulation of salmon aquaculture, as well as increased conflict between aquaculture and angling tourism stakeholders. Additionally, we briefly discuss some proposed technological and regulatory solutions to the various problems arising from salmon lice infections.

Keywords

Salmon lice, Lepeophtheirus salmonis, infection pressure, global warming, global climate change, modelling, farmed salmon, wild salmon, aquaculture, angling tourism, tourism, economic impact, property prices

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Any errors, mistakes, or misunderstandings in this thesis are entirely our own.

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1. Introduction

Salmon aquaculture is an important industry in Norway, with a strong presence in many rural and coastal areas. Since the turn of the millennium the industry has grown immensely both in terms of fish stock and in the value of the harvest (e.g. the fish slaughtered and sold)(See Figure 1 for illustration). For self-evident reasons the industry itself wants this growth to continue (Hersoug, Andreassen, Johnsen, & Robertsen, 2014), while the national government want growth both from the perspective of rural development policies (Mikkelsen, Karlsen, Robertsen, & Hersoug, 2018) and a general wish for value creation.

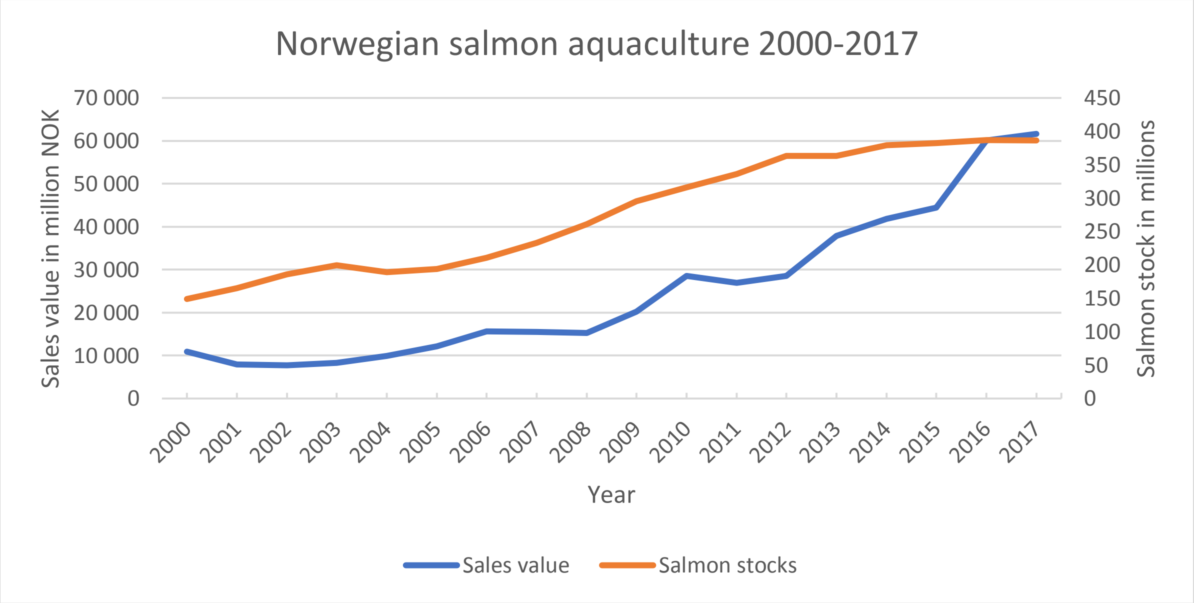

Figure 1—Graph showing the growth in Norwegian salmon aquaculture in the period 2000-20017. Left axis shows sales value in millions of NOK, while right axis shows salmon stocks in millions at the beginning of each year. Data from Statistisk sentralbyrå (2017)

In recent years this industry has been troubled by salmon lice infestations which not only leads to loss of farmed fish (Grefsrud et al., 2018), potential downgrading in quality of injured salmons (Michie, 2001), but which also causes losses from mandatory treatment once the level of infection reaches a certain level (Abolofia, Asche, & Wilen, 2017; Liu & Bjelland, 2014).

Just as worrying as the direct monetary losses is the fact that there seems to be a consensus that salmon lice from farmed salmon can affect wild salmon (Kristoffersen et al., 2018; Olaussen, Liu, & Skonhoft, 2015). This has for a long time caused great public debate (Andenæs, 2012; Olsen & Osmundsen, 2017), which again led to the institution of the “traffic light system” where various restrictions (including expansion bans) are imposed if a certain percentage of the local wild salmon is likely to die (Karlsen, Finstad, Ugedal, & Svåsand, 2016). Additionally, several important fjords and areas near vital salmon rivers have been declared off bounds for salmon aquaculture (Serra-Llinares et al., 2014). And, for a variety of reasons, including salmon lice, municipalities are growing reluctant to allocate coastal areas to aquaculture (Hersoug et al., 2014; Isaksen, Andreassen, & Robertsen, 2012).

In short salmon lice are directly harming the industry, then by extension wild salmon, and this appears to have led to a change in regulations and attitudes that are threatening the desired future growth. Anything which has a major effect on the growth rate and abundance of salmon lice is likely to either alleviate or exacerbate these issues.

It is known in general that salmon lice thrive in relatively high temperatures (Samsing et al., 2016). This has been quantified in a series of models of the fecundity, life-cycle, and infection rate and pressure (Aldrin et al., 2017; Aldrin et al., 2013; Elghafghuf, Vanderstichel, St-Hilaire, & Stryhn, 2018; Kristoffersen et al., 2014). What this suggests is that warmer seawater will lead to the salmon lice problem getting worse.

This naturally leads into the issue of global climate change which is already a major problem in many areas (Dietz, Bowen, Doda, Gambhir, & Warren, 2018; Pidgeon et al., 2017), and which is predicted to lead to increased ocean temperatures (Travers-Trolet, Sandø, Hjøllo, Skogen, & Tjiputra, 2018).

The natural conclusion appears to be that climate change has the potential to make the sea lice problem worse, both for wild salmon and farmed salmon.

To the best of our knowledge there are no studies of the topic, either from a purely biological point of view, or from an economic angle. The only exception we could find was a single sentence by Costello (2006) mentioning that global warming might affect salmon lice.

We should qualify our statements though, since there is no lack of studies on either climate change or salmon lice: both are topics that are closely studied by a great number of organisations. What seems lacking is any major study or group of researchers dealing with the combination of the two issues. Certainly, none of the researchers or organisations we contacted could inform us of such.

Since we do not have articles that have tackled these combinations before we must decide for ourselves how to do so. Our approach was to first try to create a synthesis between models describing the life-cycle and spread of salmon lice, and projected data temperature changes in the sea. For this we used the salmon lice infection pressure model by Kristoffersen et al. (2014) and got our temperature data from the ROMS (Regional Ocean Modelling System) developed by the Institute for Marine Research. For additional data we turned to Statistisk Sentral Byrå (Statistics Norway), Barentwatch (a website that contains extensive data on salmon lice), and various data sets from Fiskeridirektoratet (Norwegian Directorate of Fisheries).

Our results indicated that the increasing ocean temperatures would indeed cause the salmon lice problem to worsen, by a wide variety of metrics. This was exacerbated if we also assumed growth in the industry, as there is a close connection between the number of nearby salmon and the infection pressure (Kristoffersen et al., 2014).

Following this we wanted to demonstrate the economic effects this would have on the industry, both as a result of direct externalities (the social cost of salmon lice from aquaculture infecting wild salmon), and as a result of a changing political and regulative climate. This however was not so tractable for quantitative analysis, so we decided upon a qualitative analysis.

Our method consisted of a general literature search and short inquiries / interviews with experts in various fields. We make the caveat that for some of the issues we encounter it is possible that they have been resolved by say sociology or psychology. However, our approach has been to concentrate on engineering and economic sources and tools. When we have strayed from this, we assume that past trends will continue in the future, unless we find pressing reason to think that they will not. This applies to regulatory trends, public discourse, and the continued conflict between various interest groups.

With this approach we examined potential regulatory consequences and how the reputation of the industry might be affected, as well as externalities against other industries and areas. This included value creation from angling tourism as well as whether negative externalities harming said tourism could affect real estate prices in the afflicted areas.

Here too we found a consistent pattern of increasing negative effects as climate change heats the seawater.

Because of the complexity of this topic we have decided on limiting the scope, yet at the same time we want to show the breadth of the field. Our chosen approach is to sacrifice some depth to allow us to gain more breadth.

The first part of our thesis is reasonably conventional: Scope, background (on the history of salmon fisheries, aquaculture in Norway, and some information on salmon lice), followed by a description of how we have set up our simulation, what datasets we have used, and what assumptions we have made. We then proceed to present the result of the simulation, with some commentary on relevant background data.

We do not have a separate general theory chapter though, since theory is so inextricably linked to the subject matter that it is very hard to separate it out before going into the discussion. As such our discussion chapter contains much of our theory, interpretation of the data, and our hypothesising on how all of this will affect the political process and public discourse.

At the end we will have some topics that did not fit in elsewhere, our suggestions for future actions, and our conclusion.

2. Scope of the thesis and research question

In this thesis, we will be focussing on how temperature changes in the ocean will alter the life-cycle (maturation) and infectious population of the salmon lice. Further, we will be looking at the effects on wild salmon and farmed salmon in open fish cages at sea. Previous studies have found that on-land and closed fish farms have a negligible contribution to the salmon lice problem (Hermansen & Heen, 2012; Nilsen, Nielsen, Biering, & Bergheim, 2017), they are therefore considered outside the scope of this thesis.

We will not be seeking to directly explore potential increases in the infection rate for either wild salmon or farmed salmon. Instead, we propose to treat infection pressure (the number of present infectious adult copepods) as a proxy. However, we will justify this approach with references to literature.

Temperature will be our only variable, with other factors kept constant. These factors include: the size of the fish farms; their population; distance between aquaculture localities; growth in aquaculture; treatment regimes and developing resistance to them; and how increased salmon lice population growth is likely to lead to increased infestation rates. These are certainly important, but they are not directly connected to rising temperatures in seawater.

Salinity will also be held as a constant, but we will devote some space to explain why the projected changes in salinity (from among other things reduced sea-ice cover (Stenevik & Sundby, 2007)) will only have negligible effects.

Since we do not seek to directly simulate increased infection rates, we will use a qualitative rather than quantitative approach to economic effects. Here we are looking at three potential factors: 1. The direct economic effects on fish farms from potentially increased infection rates and pressure, including the cost of measures taken to alleviate this; 2. The socio-economic costs of increased infection pressure on wild salmon; 3. Likely political and regulatory changes, by extrapolating past trends given this additional information. The latter will also look at public discourse and relations between regional and national stakeholders.

3. Background

In this chapter we will present a brief overview of the histories of salmon fishing and aquaculture in Norway. We shall show that the social and economic importance of the wild salmon has always led to quarrels over fishing rights and conservation measures. In that regard the aquaculture industry is simply the latest party to this ancient conflict.

We shall follow this with a brief description of sea lice and the adverse effects of sea lice infestation.

3.1. Brief historical overview of salmon fishing in Norway

The best place to begin explaining the importance of the salmon (*salmo salar*) to the Norwegian people is to look at its lifecycle and migration pattern. Excepting artificially hatched fish, a wild salmon is hatched in a salmon river, which are the breeding grounds of the salmon. For several years it lives in the river, growing larger, before finally migrating out to sea where it grows into sexual maturity (Otero et al., 2014). After reaching sexual maturity the salmon will instinctively return home for mating season. (Karlsen et al., 2016) The predictability of this mating season, and the vast schools of salmon it brought, made salmon fishery a vital and reliable source of food for the people living by Norwegian fjords and rivers. (Berg, 1986)

This early salmon fishery was, as far as we can tell, entirely food related. Waiting along the length of the river the fishers used whatever tools were at hand from fish-spears and tridents in earlier days, to throwing nets and seine nets as time went by (Solhaug, 1983). However, as we see in Berg (1986), even very early on there were regulations: in the old Gulating legal code the landowner kept his traditional rights to fish, even with standing nets, but was banned from blocking the river. Meaning to stretch nets across the breadth of the river, which would prevent migrating salmon from reaching the farms further upstream. However, this was more about preserving traditional rights than conserving fish stocks, as can be seen from how this right was phrased: “God’s gift shall wander freely to the mountains as well as to the strand”. Since these rights were usually held by landowners, we see the strong link between fishing rights and real property. (Berg, 1986)

One illustration of this abundance comes from anecdotes from the area around certain large salmon rivers in Norway. The details may vary, but the gist of it is that the farmworkers near salmon rivers had it in their contract that they could only be fed salmon a certain number of days a week. Whether this is true or not, it shows that the abundance of the sea is still strong in folklore.

What is certain is that between the 1660s and 1850s Norway’s population almost quadrupled (Statistisk sentralbyrå, 2018b). As we see in Solhaug (1983) this was combined with declining costs for nets from the 1830s onwards. The result was increased pressure on Norwegian salmon rivers, in several places the river mouth was blocked by gillnets set by landless workers and small farmers living nearby. Attempts to resolve the issue by using the traditional Norwegian laws failed, so the problem was brought before parliament and the King. The main instigators of this effort were of course landowners living by the river, especially those landowners which were situated higher up the river. Again reinforcing the idea of fishing rights as property rights (Solhaug, 1983).

Though the landowners only wanted to protect their property rights, there was even early on an attempt to use these laws to conserve stock and improve fisheries (Solhaug, 1983). Berg (1986) explains that professor H. Rasch was instrumental in describing the damage caused by industry (like watermills), permanently gillnets, harpooning salmon during mating season, and a series of other issues. Likewise, there was a lively debate on whether spearfishing with artificial lights should be banned, since this form of fishing not only interfered with breeding but often killed the fish without catching it (Berg, 1986). It would perhaps be too much to call this environmentalism and concern for animal welfare, but one can see that these issues have deep roots.

Solhaug (1983) tells us that in 1848 the first series of regulations were passed, another came in 1857. Their purpose was to conserve the stock of salmon, while at the same time making sure that the catch was equitably divided between landowners upstream and downstream. Throughout this process there was a need to grant exemptions and incentives to make local landowners co-operate with the new regulations. For instance landowners kept the right to use fixed nets, but at the same time the government reinforced the claims of upstream landowners by reference to the fact that the salmon mated in the uppermost reaches of the river. (Solhaug, 1983)

It did now however end there as there were further regulations in 1863, 1866, and 1869, all of which added new restrictions to how and when the salmon could be harvested (Berg, 1986). As Solhaug (1983) tells us this of course was about the same time as steam-ships came into their glory days, which gave Norwegian access to Scottish ice and faster transportation. As a result, salmon seemed to change from a local food-source to an export good that would bring in hard currency, as well as foreign sport-fishers (Solhaug, 1983). This coincided with the invention of the salmon trap (or bag-net) which at times greatly taxed the salmon population, causing increasing tension between sea-fishers and river-fishers. (Berg, 1986)

One more actor was about to come on the stage, namely the sports-fisher. Initially these were a collection of British businessmen, natural scientists and explorers who sought out the Norwegian salmon rivers (Berntsen, 1990). From Solhaug (1983) we see that sport-fishing became more popular the value-creation in these rivers shifted from renting out their fishing rights, rather than using it to extract salmon directly. Starting in the 1860s this became a considerable source of income for the landowners. Even though these Englishmen often insisted that net-fishery be reduced or eliminated, the loss of income from the salmon harvest was more than made up for by the tourist-income. For instance, already in 1864 one set of fishing-rights in Lågen were leased for 800 *speciedaler* (Solhaug, 1983) It generally known that it is hard to translate historical prices into modern ones, but for the period this sum was the equivalent of the annual income of a skilled carpenter (Statistisk sentralbyrå, 2018a). In other words, even from early days this was a very large source of income for many farmers along the salmon rivers.

This can be said to be the beginning of the modern age of Norwegian salmon fisheries. The same pattern of conflict between these interest groups, of increasing tourism and regulations, would continue unabated until the present day (Berg, 1986). The conflict is well described by this quote:

> *The salmon is a considerable asset for our country, and by way of legislation it is sought to preserve and use this asset. Our legislature encounters great difficulties in solving this task, but it may be comforting to know they are not alone in this regard. In the English parliament the law that holds the record for the number of times it has been brought up and revised, is precisely the laws regarding salmon fisheries. These difficulties are quite evident. On its way to its mating grounds the salmon passes everyman's door, and everyone wants to take it. The fisher out at the coast, the landowners by the fjord, the farmers by the river, all of them want to strike the silver of the sea into coin, and for this part of our population the chance to get hold of cash is both rare and welcome.*

> *The task of the authorities is to, within the bounds of reason, to let them have their way, and the bounds of reason are what they must draw up. Theoretically these bounds of reason are between capital and interest, between the population and the annual catch. The capital must be preserved if the annual income is to be cashed out.* (Brekke, 1940)(Trans: Ours)

Even in the 1940s it was pointed out that Norway had the potential to be a veritable paradise on Earth for sports-fishers, if only the government and the landowners could all work together (Brekke, 1940). From Berg (1986) we see that this hope proved illusory for a long time, the conflict continued even as the increasing value of sports-fishing meant that commercial fisheries in the rivers were forced to marginal locations. The conflict of interest between riverine landowners and sea-fishers were not so easily resolved, as the sea-fishers were often quite well organised unlike the landowners (Berg, 1986). In recent years there has been some work to help landowners organise themselves further, while at the same time resolving the arguments with sea-fishers. For instance pilot programs to buy-out sea-fishers, that is to pay them for not catching salmon. (Kjelden et al., 2012). Fishing rights is in other words still very much a live political issue, which is tied very closely to tradition, real property, and real income.

3.2. Brief historical overview of salmon aquaculture in Norway

Since we have Viking age runestones informing us of who carried fish into certain waters, it might be tempting to argue that aquaculture goes back into prehistory (Berg, 1986). Others might link it to the attempts at artificially hatching salmon eggs, a practise that went on from the 1850s to the end of the 1800s. (Solhaug, 1983) However it seems better to start it with attempts to raise fish in artificial enclosures in order to harvest them directly for food.

Going from Lysø (1977) it seems that we should look at the attempts pioneered by Professor Rasch and Magnus Hetting (the first Norwegian fisheries inspector) to hatch fish in fresh water, before releasing them into closed of dams of salt-water where they could be fed and harvested when they had grown large enough to be food. Over decades there were repeated attempts, with the last facility built in 1875, but despite these efforts the technology of the day was simply not up to the task. Another series of attempts in the 1910s failed for similar reasons (Lysø, 1977).

Another set of attempts were made in the 1950s, where an artificial dam was built in Kragerø to raise rainbow trout, but this too proved unprofitable and was shut down (Lysø, 1977).

Despite these discouraging failures interest remained high, perhaps as a result of success abroad, and attempts continued into the 1960s and 1970s (Berg, 1986; Lysø, 1977). There first real breakthroughs were in 1968 and 1970 when Mowi A/S and the brothers Sivert and Ove Grøndtvedt respectively started their aquaculture operations (Berg, 1986).

Since then the aquaculture industry has expanded rapidly, with an accompanying increase in regulations (Mikkelsen et al., 2018).

However negative side-effects of the industry have led it into increasing conflict with environmentalists, salmon fishers, landowners and angler tourists. This is a conflict that is often harshly expressed (Osmundsen & Olsen, 2017), and like previous conflicts surrounding salmon this one is also deeply rooted in real conflicts of interest (Stensland, 2010; Tiller, Brekken, & Bailey, 2012).

The aquaculture industry is in short part of a great chain of people trying to profit from the bounty of the sea, but in doing so coming into conflict with other interests.

3.3. Brief background on the salmon lice problem

Salmon lice (*Lepeophtheirus salmonis* Krøyer, 1838) is a seaborn parasite that is endemic to salmonids (Karlsen et al., 2016). It has a total of ten life phases, during which it changes both properties and appearance. These stages are as follows: nauplius (I & II), copepodid, Chalimus (I, II, III & IV), pre-adult (I&II) and adult (male and female) (Schram, 1993), see Figure 2 for illustration.

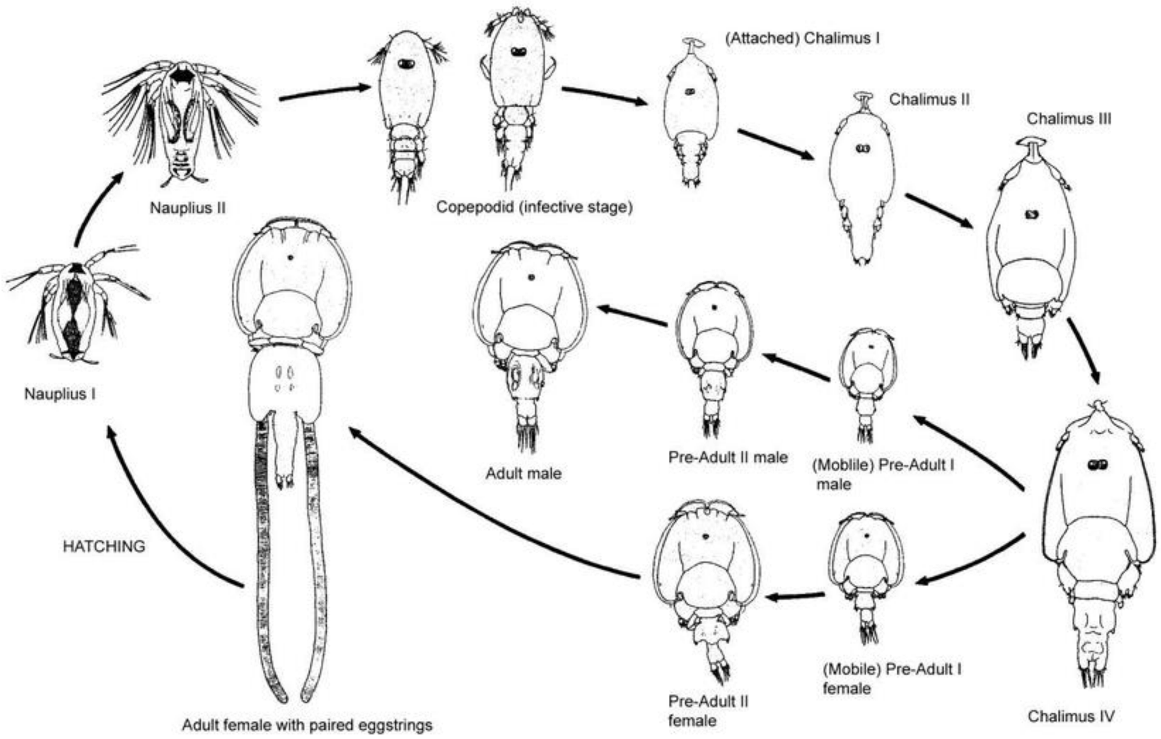

Figure 2—Life cycle of the salmon lice (Lepeophtheirus salmonis) after Schram (1993).

From Revie, Dill, Finstad, and Todd (2009) we read that nauplius and copepodite stages drift passively (with only the ability to adjust their depth), the neither feeds, but develops and survives using stored energy. Once it reaches the infectious copepodite stage it will then attempt to latch onto a host, presumably by drifting near one and latching onto it. Despite this lack of mobility it is exceptional in being one of very few parasites to reach a 100% infection rate in the wild, something that is nearly unheard of (Revie et al., 2009).

Once it has infected a host the salmon lice begins to feed of its muscle, skin, slime and blood (Grefsrud et al., 2018), which hampers the salmon’s ability to swim and increases the cost of osmotic regulation (Revie et al., 2009), and can also work to provide room for additional bacterial or fungal infections (Grefsrud et al., 2018; Revie et al., 2009). It is particularly the sexually immature salmon (smolt), migrating from their birth river, who are vulnerable to infection (Karlsen et al., 2016), and a number of infections that would be safe for an adult might easily kill a smolt (Olaussen et al., 2015).

Since Norwegian salmon aquaculture revolves around open net cage salmon farms, with a free exchange of water, the parasite has free access to a much larger population. Although the farms themselves rarely exceed certain levels of infections per fish, sheer numbers (there are

500 times as many farmed salmons as wild) means that they constitute a significant infection vector for wild salmon (Grefsrud et al., 2018; Revie et al., 2009).

Salmon lice infection pressure caused by the open cage fish-farms is not just a problem to salmon aquaculture (Grefsrud et al., 2018), but is considered to either be the proven cause of decreased wild salmon stocks (Anon, 2014; Olaussen et al., 2015) or else a very likely cause of stress on the wild salmon population (Revie et al., 2009). Given the desire of the industry to continue expanding (Hersoug et al., 2014; Kvalvik & Robertsen, 2017) and the increasing value of angling tourism (Kjelden et al., 2012; Stensland, 2013) the problem is already the cause of significant controversy.

It is no wonder salmon lice has become a serious problem for salmon aquaculture (Grefsrud et al., 2018; Revie et al., 2009). Especially since we are experiencing an increase in salmon lice resistance to chemical treatment, as well as greatly increased regulations (Nilsen et al., 2017).

We have already mentioned that climate change is predicted to lead to an increase in the sea temperatures along the Norwegian coast (Travers-Trolet et al., 2018). Which given the salmon lice preference for higher temperatures (Samsing et al., 2016) is likely to exacerbate the problem. Figure 3 gives a direct example of this, by showing the time it takes to go from a salmon lice egg to a sexually mature adult given a certain temperature.

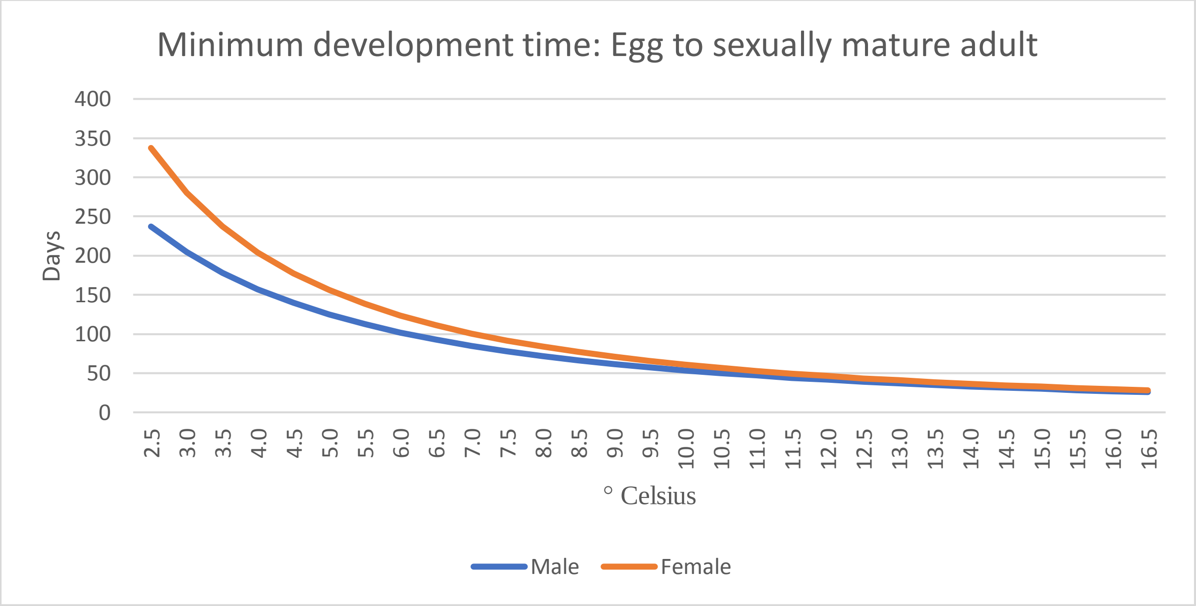

Figure 3 – This graph shows how many days it takes to go from a salmon lice egg to a sexually mature adult given a set temperature. Both male and female development times are shown. Development times given temperature comes from Stien, Bjørn, Heuch, and Elston (2005).

4. Simulation of salmon lice infection pressure

In this chapter we will look at the theoretical model for how temperature affects salmon lice, and therefore contribute to the infection problem mentioned in chapter 3. We explain what simulation model we picked and why, as well as describe some of the assumptions and simplifications we are making. Further, we will briefly go over some of our datasets and, where relevant, explain how we have processed them for use in this thesis.

4.1. Chosen salmon lice model

A considerable number of number of models have been developed to describe everything from salmon lice reproductive and maturation rates (Stien et al., 2005), to infection rates at individual salmon farms (Aldrin et al., 2017), to modelling monthly abundance and spread (Aldrin et al., 2013), and to how they are influenced by seasons (Rittenhouse, Revie, & Hurford, 2016). We even found a study that looked into the salmon lice induced mortality of seaward-migrating post-smolt Atlantic salmon (Kristoffersen et al., 2018), a very important aspect of the economic impact of salmon lice.

We settled on using the model presented in "Large scale modelling of salmon lice (*Lepeophtheirus salmonis*) infection pressure based on lice monitoring data from Norwegian salmonid farms" (Kristoffersen et al., 2014). There are several reasons for this choice:

- The model accounts for the temperature over previous weeks and months.
- It can be quickly adapted to any defined locality.
- It relies exclusively on distance to calculate the influence of nearby aquaculture facility.
- For our purposes it can be very flexible about what values are variables and which are constants.
- Since infection pressure is a threat to both farmed salmon and wild, the same model can inform us about the threat to both.

Infection pressure is here defined as the amount of infectious copepodites present within a locality. In this thesis locality is generally used to designate an area set aside for aquaculture, but, in this chapter, we may also use it to mean a general area of ocean the size of an aquaculture locality. The more copepodites present in a locality the greater the risk of infection for both farmed salmon (Jansen et al., 2012) and wild salmon (Kristoffersen et al., 2018). For our purposes this makes infection pressure a good proxy for the general threat level to both farmed and wild salmon.

Kristoffersen et al. (2014) also uses the terms External Infection Pressure (EIP) and Internal Infection Pressure (IIP). Internal Infection Pressure is the contribution that the locality itself makes to the local copepodite level. External Infection Pressure is the contribution of surrounding aquaculture localities to the copepodite level of the measured locality.

In order to explain how we find the EIP and IIP we will present the equations from Kristoffersen et al. (2014) article, with brief explanations of the terms. Unless explicitly noted all the equations and explanations are from Kristoffersen et al. (2014), with direct quotes in "- ".

$$(1)\ F = \frac{300\ eggs}{\left(\frac{41.98}{T - 10 + (41.98 * 0.338)}\right)^2}$$

F (fecundity) "is defined as the daily production of newly hatched salmon lice larvae from an adult female lice."

T: is temperature (°C)

$$(2)\ \Delta t_{PI} = \frac{125\ degree \cdot days}{T\ degrees}$$

Δt_{PI}: The time it takes to pass through the pre-infective stages.

Note: This is one of the areas where we deviate from the main model, in that the original number was 35 degree-days, but it has been raised to 125 to make the model better fit empirical data (Aldrin, 2016).

$$(3)\ S_{PI} = (1 - 0.17)^{\Delta t_{PI}}$$

S_{PI}: The proportion of the population that survives through the pre-infective stage.

$$(4)\ \Delta t_{CH} = \frac{155\ degree \cdot days}{T\ degrees}$$

Δt_{ch}: The time it takes to pass through the chalimus stages.

$$(5)\ S_{CH} = (1 - 0.05)^{\Delta t_{CH}}$$

S_{ch}: The proportion of the population that survives through the chalimus stages.

$$(6)\ RR_{ij} = \frac{exp\left(-1.444 - \frac{d_{ij}^{0.47} - 1}{0.57}\right)}{exp\left(-1.444 - \frac{d_{jj}^{0.47} - 1}{0.57}\right)}$$

RR_{ij}: “The relative risk for infective [copepodites] produced at farm *j* to contribute to infection pressure at location *i*.”

d_{ij}: Distance in kilometres between locality i and locality *j*.

d_{jj}: Distance in kilometres between locality j and locality *j*. Presumed to be 0.

$$(7)\ IIP_{i.day} = \sum_{\Delta t^*} A_{AF,i,(day-\Delta t_{PI,i}-\Delta t_{CH,i}-4)} n_{fish,i,(day-\Delta t_{PI,i}-\Delta t_{CH,i}-4)} F_{i,,(day-\Delta t_{PI,i}-\Delta t_{CH,i}-4)} S_{PI,\Delta t_{PI,t}} S_{CH,\Delta t_{CH},i}$$

$\mathrm{A_{AF}}$: “Reported adult female lice abundancy on the farm”.

$\mathrm{n_{fish}}$: “Number of fish on the farm”.

Δt^*: “Represents all timepoints $\Delta t_{PI,i} + \Delta t_{CH,i} + 4$ that contributes with copepodids to the given day.”

$$(8)\ \mathrm{IIP_{i,t}} = \sum_{day \in t} IIP_{\mathrm{i.day}}$$

$\mathrm{IIP_{i,t}}$: “To obtain IIP on a weekly basis the daily IIPs were summed for all weekdays t”.

$$(9)\ \mathrm{IP_{j,t}} = \sum_{\forall i} IIP_{\mathrm{i.t}} RR_{ij}$$

IP: “The total infection pressure (IP) on site *j* is then found by weighting all internal infection pressures from all farms within 100km by the formula”.

$$(10)\ \mathrm{EIP_{j,t}} = \mathrm{IP_{j,t}} - \mathrm{IIP_{j,t}}$$

EIP: External Infection Pressure.

There is great additional depth and explanation of the model in Kristoffersen et al. (2014), but we believe this abbreviated version is sufficient for the purpose of this thesis.

4.2. The virtual area used in the simulations

Other variables that need to be accounted for are: The number of fish-farms nearby (and their distance from the measured locality); the quantity of salmon in each fish-farm; and the frequency of female lice in each fish-farm. However, we did not want to limit our study to one particular, actual area, but rather create a virtual area that is representative for fish-farming areas on the Norwegian coast. The reason being that this would let us test this virtual area against projected climate data regarding different parts of the Norwegian coast.

The Norwegian Directorate of Fisheries maintains a map service called Yggdrasil (. Fiskeridirektoratet, 2019), from which it is possible to download datasets about Norwegian fisheries and aquaculture. We downloaded a GML (a variant of XML) dataset containing all the data on Norwegian aquaculture facilities. This includes such factors as their geographical location, their designated use, and the maximum total biomass (MTB, which will be explained in greater detail later).

An immediate problem was that it was hard to find which localities were being used by which permits at any one time. Here a permit refers to a permission to run a fish-farm, while a locality refers to areas cleared for aquaculture. This is an issue since each permit can be used in four localities (six if multiple permits are using those localities), (Mikkelsen et al., 2018). We therefore decided to operate with localities instead of permits and individual fish-farms.

Consequently, we wrote a MATLAB script to extract the data from the GML file, choosing localities with permits designated as salt-water and for commercial rearing of salmon for consumption. This had the effect of leaving out some experimental facilities, but these were small in scale, and often operated with number of fishes instead of tons of biomass (thus creating potential consistency issues). The end result was 896 localities, we know that in 2014 there were 943 cleared localities (Hersoug et al., 2014), and so this result seems reasonable.

We used another MATLAB script to compare the relative distances between every single locality, using Haversine formula for calculating distances between two points on the globe. One weakness is that this means some of these measurements would go over land, but since the model we use only takes into account facilities within a 100 km radius (Kristoffersen et al., 2014) this seemed acceptable.

One problem is that the localities are at greatly varying distances from each other, which would complicate our model. We decided to model our virtual area as having one locality in the middle, surrounded by concentric rings at set distances, with neighbouring localities placed on one of these rings. The distances we picked was 5, 10, 20, 40, 60, 80 and 100 km. Localities 5 km or less apart count as being 5 km apart, between 5 km and 10 km as 10 km apart, and so on. We then took a rounded mean of all the localities to see how many neighbouring localities the "average" locality would have, and at what distances. This resulted in a virtual area illustrated in Figure 4.

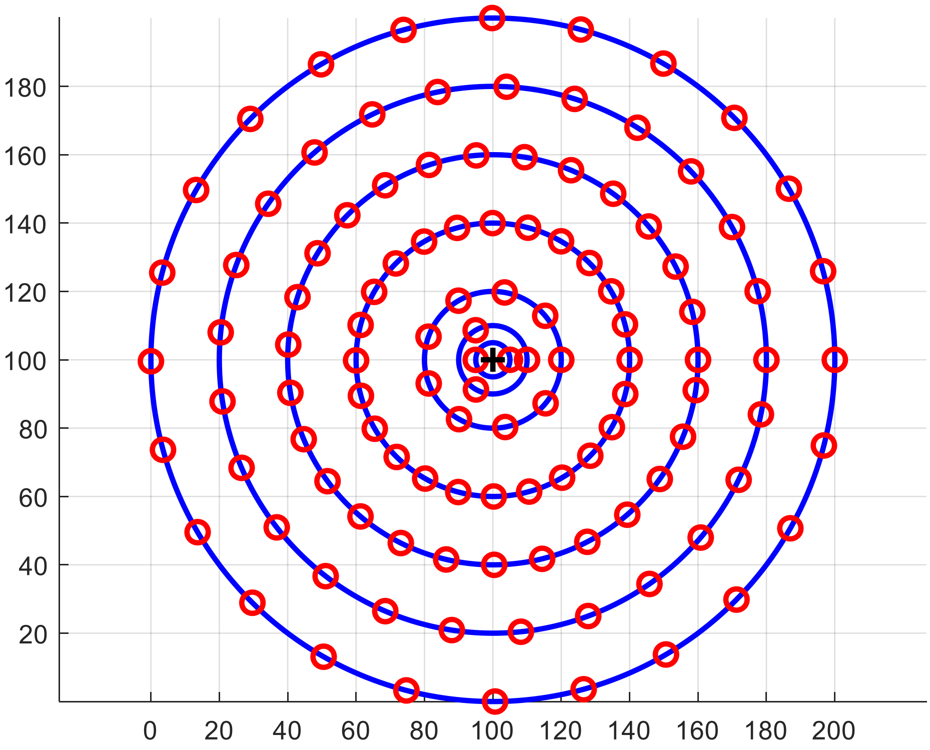

Figure 4 – Blue circles are drawn at respectively 5, 10, 20, 40, 60, 80 and 100 km from our central locality (the cross), red circles are other localities. Co-ordinate system is in kilometres. Starting at the 5 km circle and moving outwards there are respectively 2,3,9, 24, 27, 25, and 24 localities.

For simplicity we will assume that these localities are all identical, do not change fish stock over the year, and do not influence each other. However, the literature clearly mentions that the life-cycle of the salmon lice is affected by the seasons (Grefsrud et al., 2018; Pike & Wadsworth, 1999), indeed we know that infection rates vary over the year (Aldrin et al., 2013). Upon downloading and analysing the Barentswatch dataset on salmon lice infection rates (Barentswatch, 2019) we found by way of graphical analysis that this held true.

To find the weekly average infection rate for the period 2013-2018 (counting inclusively) we used the following method:

$$(11)\bar{w}_i = \frac{\sum_{y=2013}^{2018}\sum_{j=1}^{N_{y.i}} w_{y,i,j}}{\sum_{y=2013}^{2018} N_{y,i}}$$

Where $\bar{w}_i$ is the weekly average for week i, where $i \in \{1,2,\dots,52\}$.

j is a locality for which a lice-count has been made.

$N_{y.i}$ is the number of localities counted for week i in year y.

We then assume that the weekly averages $\{\bar{w}_1, \bar{w}_2, \dots, \bar{w}_{52}\}$ are, for the purpose of our simulation, the actual infection rate for the relevant week for all years 2013-2069. And we present our graph (Figure 5):

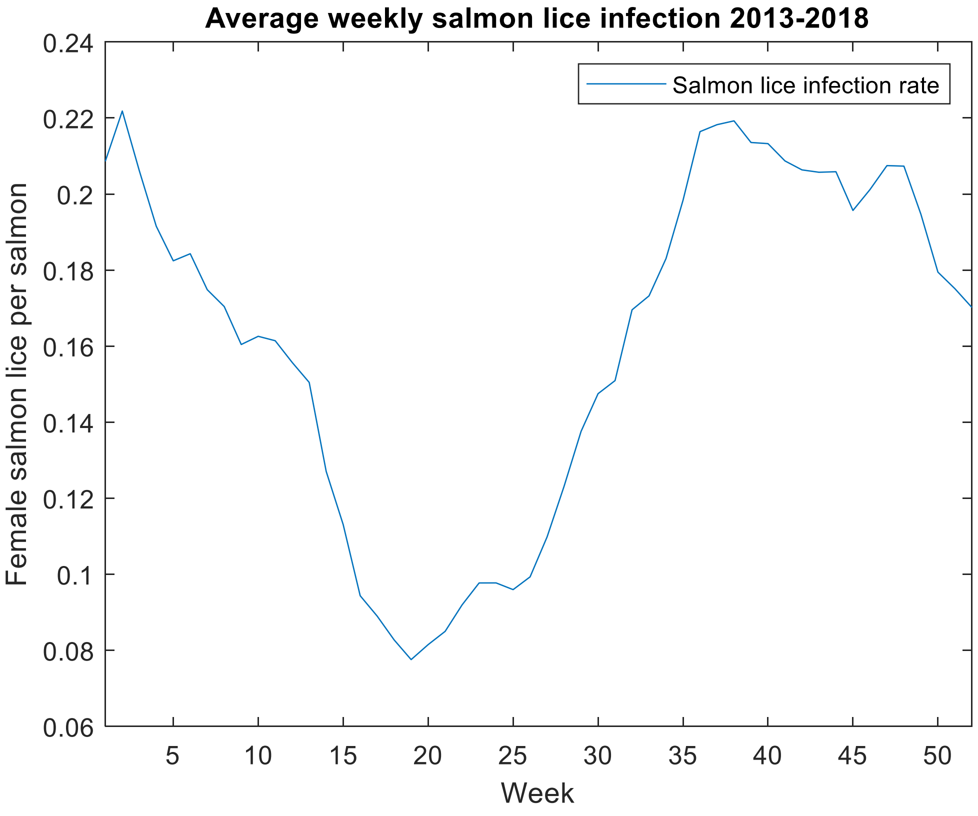

Figure 5 – Average weekly salmon lice infection based on Barentswatch data (Barentswatch, 2019)

We then checked against statistics for total fish-stocks in terms of number of fish, and found that in 2017 the total quantity of salmon stock was 427 982 000 (Statistisk sentralbyrå, 2017). This amount was divided by the number of localities to find how populous each locality would be.

Thus far we have accounted for the variables RR_{ij}, A_{AF} and n_{fish}, but we still need to find T.

4.3. Temperature change model

Perhaps the most important variable that needs to be accounted for is the temperature (T). Since we are explicitly doing a simulation to see the effects of global warming, we need a projection of how global warming will affect the ocean temperatures on the Norwegian coast. This caused some difficulties as the bulk of the projections we found were either too coarse in terms of time (covering years or decades) or in terms of geography.

We contacted Havforskningsinstituttet (eng: Institute of Marine Research) who had a variant of ROMS (Regional Ocean Modelling System) developed for the Norwegian coast. The original ROMS system is described by Shchepetkin and McWilliams (2005) as a hydrodynamic kernel that uses numerical processing. More usefully Todd et al. (2014) describes it as a means to simulate regional ocean currents and hydrography. The version whose results we got access to was very well described by Travers-Trolet et al. (2018) which explains the precise climate change model it operates under and how overall the model has been adapted to provide good projections of, among other things, salinity and temperature at various depths along the Norwegian coast.

Further Lien, Budgell, Ådlandsvik, and Svendsen (2006) inform us “A 25 year hindcast carried out with the model ROMS (Regional Ocean Modelling System) is validated by a quantitatively comparison between the model results and observations on temperatures and volume transports in the Nordic Seas.” That is a hindcast of the period 1981-2006 was compared to real data. The results showed that the model predictions were very close to observed temperatures, which means that within its limits the ROMS model is reasonable accurate (Lien et al., 2006).

We did not at any point access the actual model but were, very gracefully, given the data we required for a set of specified co-ordinates (more on this below).

4.4. Implementing the infection pressure simulation

4.4.1. Virtual Area Locations (VAL) selected

It is generally known that temperatures along the Norwegian coastline, especially ocean temperatures, vary greatly from north to south. Likewise, the data from the ROMS model show that temperature increases are both absolutely and relatively greater in the north than in the south. So, we decided to do our simulation against temperature data from four different locations on the Norwegian coast.

For convenience we named these locations: Bergen (60°11’ N, 5°12’E), Trondheim (63°49’ N, 8°, 32’E), Helgeland (66°3’ N, 12°, 7’E), and Lofoten (68°3’N, 13° 45’ E), based on the nearest city or region. When we use the names Bergen, Trondheim, Helgeland and Lofoten it simply means that we have placed our virtual area (see Figure 4) centred at the co-ordinates mentioned above in a virtual area location (VAL).

The data we received for these co-ordinates was salinity and temperature for each month over the period 2010-2069, but at 0m and 5m depth. We used interpolation to find temperature and salinity at 3 m depth.

4.4.2. Relative changes from baseline year

To examine the effect of global warming over time, we will compare each year in the ROMS temperature data with a baseline year. To create the baseline year, we take average temperatures for each month from 2013-2018 (with temperature data from ROMS), thus:

$$(12)\ \bar{T}_{m,i} = \frac{\sum_{y=2013}^{2018} T_{m,i,y}}{6}$$

Where $\bar{T}_{m,i}$ is average monthly temperature for the virtual area location i, and $m \in \{1,2,\dots,12\}$, covering January-December, and y is the relevant year (2013-2018, counted inclusively).

Our reasoning is that nothing is as representative of our current climate as our current climate, even if it is our simulated current climate. In those cases where the model requires that we refer to dates in previous years (Kristoffersen et al., 2014) we decided that our simulation would simply loop around into the end of the baseline year.

There are now two models for making comparisons:

1. Create a baseline year for each of the four virtual area locations. Then, for each VAL compare the baseline year against the simulated years for the period 2013-2069 and show the difference in terms of percentage (positive or negative).

$$(13)\ \%Change_{Y,i} = \frac{EIP_{Y,i} - EIP_{baseline,i}}{EIP_{baseline,i}} \cdot 100$$

Where $\%Change_{Y,i}$ is percentage change for EIP_Y (External Infection Pressure [EIP] for year Y and VAL i) compared to $EIP_{baseline}$ (EIP for the baseline year for VAL i)

2. Create a baseline year for Bergen. Then set the infection pressure (see section 4.1) for the Bergen VAL in the baseline year as 100, before comparing simulated years for the period 2013-2069 for each VAL, like so:

$$(14)\ RelativeEIP_{Y,i} = \frac{EIP_{Y,i}}{EIP_{baseline,Bergen}} \cdot 100$$

Where $RelativeEIP_{Y,i}$ is how large the EIP of VAL i in year Y is compared to the EIP of Bergen in the baseline year.

4.4.3. The simulated year

One of the issues we face is that ROMS data gives monthly temperatures, and the salmon lice date is given per week. Meanwhile Kristoffersen et al's (2014) model depends on daily data. We simplified by assuming that each day in the month had the same temperature, while each day in each relevant week had the same infection rate. Or to simplify using Table 1:

Table 1—Month, Week, Day table for demonstration purposes.

M	January							February			…	November			December						
W	1			…	4	5					…	48					49	…	52		
D	1	2	3	…	28	29	30	31	32	33	…	332	333	334	335	336	337	…	362	363	364

Day 30 would have the temperature of January and the lice-count of Week 5, while day 31 would have the temperature of February and the lice count of Week 5, and so on.

This does introduce some inaccuracies, among other things we are now operating with a 364-day year. However, since we wish to compare trends and changes, rather than find absolute values, we judged the impact on our simulation to be negligible.

4.4.4 Raw temperature data and temperature data from linear regression

All of our simulations use either raw temperature data (from ROMS) or temperature data from linear regression (of the ROMS data).

Raw temperature data is easily explained: We take the temperature projections directly from the ROMS data file and insert them into our model.

Temperature data from linear regression comes by taking a linear regression of the ROMS data for each month across the timespan 2013-2069, so that the temperature for each month is:

$$(15)\ T_{m,i,Y} = \alpha_{m,i} + \beta_{m,i} \cdot (Y - 2013)$$

Where $T_{m,i,Y}$ is temperature for month m (where $m \in \{1,2, \ldots 12\}$), i is the VAL, and Y is the year. Likewise $\alpha_{m,i}$ is the initial temperature for month m and VAL i. $\beta_{m,i}$ is the growth rate for the month m and VAL i, again Y is the year.

4.4.5 Steady state vs growth

In our initial set of simulations (both raw data and linear regression) we assume that the production of salmon would remain constant, and therefore the number of fish would remain constant. However, production is set to triple between 2014 and 2030, and quintuple by 2050 (Hersoug et al., 2014), which means we ought to take potential growth in the biomass into account.

We will assume that the production will quadruple (300% increase) between 2018 and 2069, and that there will be steady annual growth from 2018 onwards. This requires an annual increase of 2.76% in the number of salmon in each locality.

4.4.6 Changing the virtual area

We will also be conducting some tests where we change the layout of the virtual area (move some localities or flat out eliminate some of the concentric rings and the localities there). This is to see how distance affect infection pressure, and to what degree sheer biomass can overcome distance. We will go into more detail in chapter 5.

5. Results of the simulation with brief review of underlying data

In this chapter we will present the results of the simulations discussed in chapter 4. When doing so would reveal something of interest, we will also look at some of the underlying data. Discussions and interpretations will be reserved for chapter 6.

As mentioned earlier when we refer to Bergen, Helgeland, Lofoten and Trondheim these are merely Virtual Area Locations (VAL), see section 4.4.1. for details. Further as mentioned in section 4.4.2 the comparison is always against a baseline year.

5.1. Percentage change in EIP given steady state

Our initial comparison (Figure 6) is of the percentage change in EIP (see section 4.4.2 "Relative changes from baseline year", we are here using the first model for comparison), given a steady state (see section 4.4.5 "Steady state vs growth"), and using both linear regression temperature data and raw ROMS temperature data (see section 4.4.4 "Raw temperature data and temperature data from linear regression")

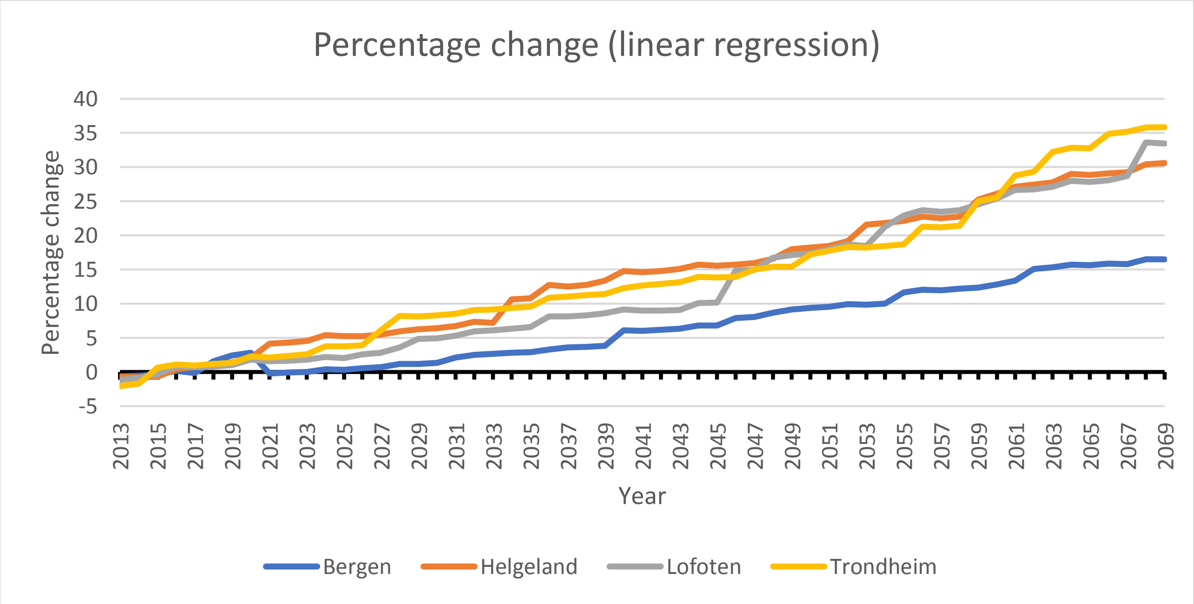

Figure 6 – Percentage change in infection pressure with monthly linear regression for the temperature.

In Figure 6 we immediately note a steady upwards trend over time, without any big surprises. Given a positive growth rate β for temperature on most months (see section 4.4.4, as well as Figure 14 in section 5.5 "How does monthly average temperatures change over time?") this is more or less what we would expect.

That picture changes when we turn to the simulation using raw ROMS temperature data (Figure 7):

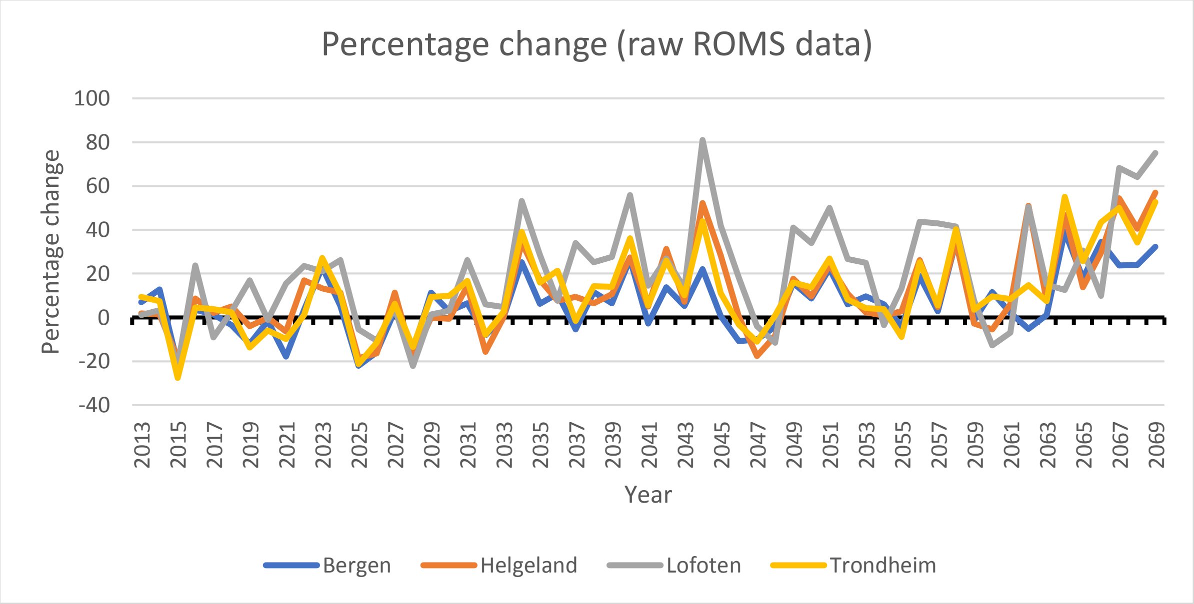

Figure 7- Percentage change in infection pressure over time given raw ROMS temperature data.

We see a series of ups and downs, revealing the chaotic nature of weather. Now of course, as we know from both (Travers-Trolet et al., 2018) and (Slingo & Palmer, 2011) these are projections, so although we can be reasonably certain of the upwards trend, we cannot tell what any particular year will actually be like.

5.2. Relative infection pressure given steady state

Our next comparison is of the relative EIPs (see section 4.4.2, we are here using the second model for comparison), given a steady state (see section 4.4.5), and using both linear regression temperature data (Figure 8) and raw ROMS temperature data (Figure 9) (see section 4.4.4). The question we are asking here is: "How severe is the infection rates relative to each other."

We initially make the comparison using temperature data from linear regression:

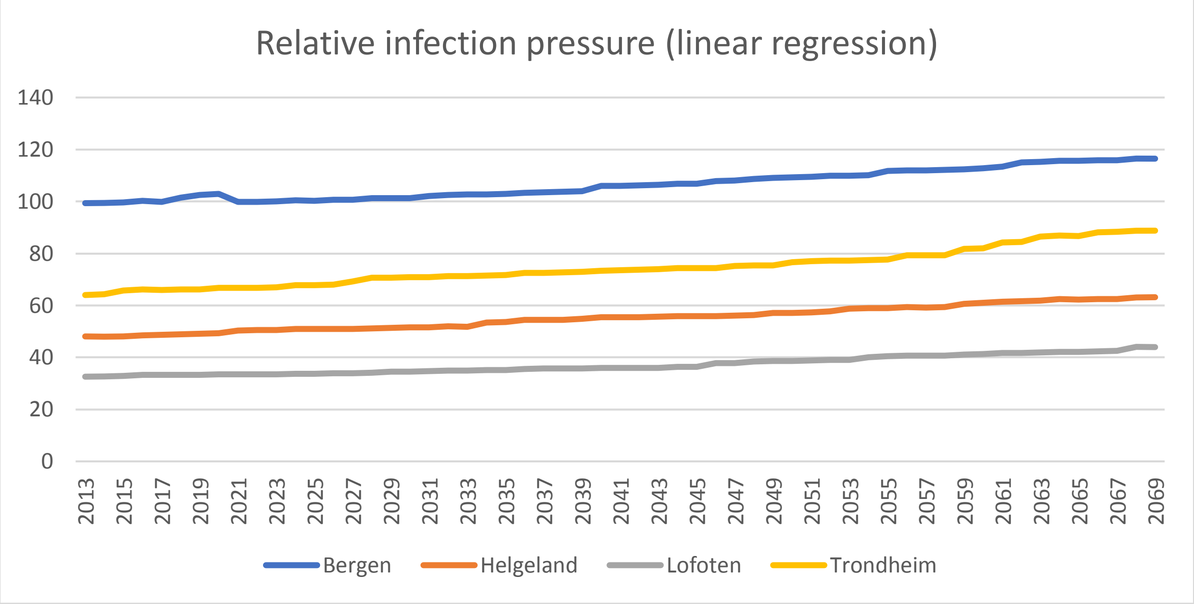

Figure 8 – Relative infection pressure (Linear Regression)

Again, in Figure 8 we see that we have a gentle upwards slope without much in the way of bumps or sudden increases. Once more this changes when, in Figure 9, we apply the raw temperature data:

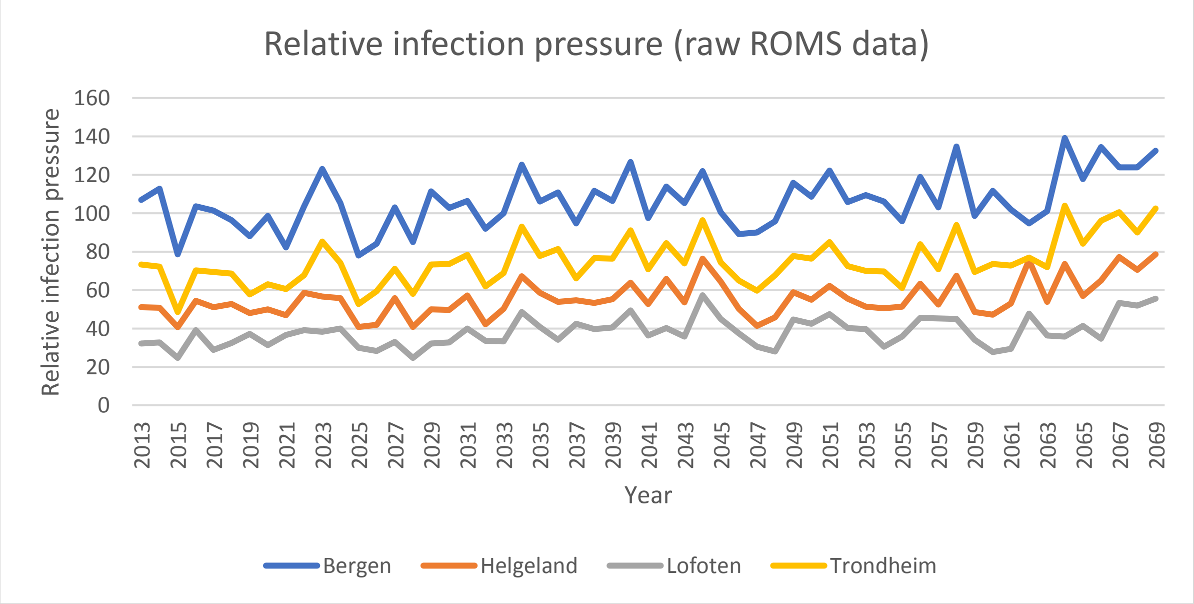

Figure 9 – Relative infection pressure (raw ROMS data)

In Figure 9 we note that Lofoten VAL retains the lowest relative infection pressure, even though it also has the highest growth in infection pressure. We do however see that the infection pressure is increasing in absolute terms, since all VALs have an upwards trend in our charts). Again, it is obvious even from cursory inspection that the raw data gives far more extreme results.

5.3. Percentage change in EIP given steady state

As mentioned in chapter 4, we should look at what happens if the industry has the growth that it wants (Hersoug et al., 2014). Thus, we will now carry out a simulation that assumes annual 2.76% growth in farmed Atlantic salmon biomass (for which we use fish numbers as a stand-in) in all localities.

Our next comparison is of the percentage change in EIP (see section 4.4.2, we are here using the first model for comparison), given growth in biomass (see section 4.4.5), and using both linear regression temperature data (Figure 10) and raw ROMS temperature data (Figure 11) (see section 4.4.4)

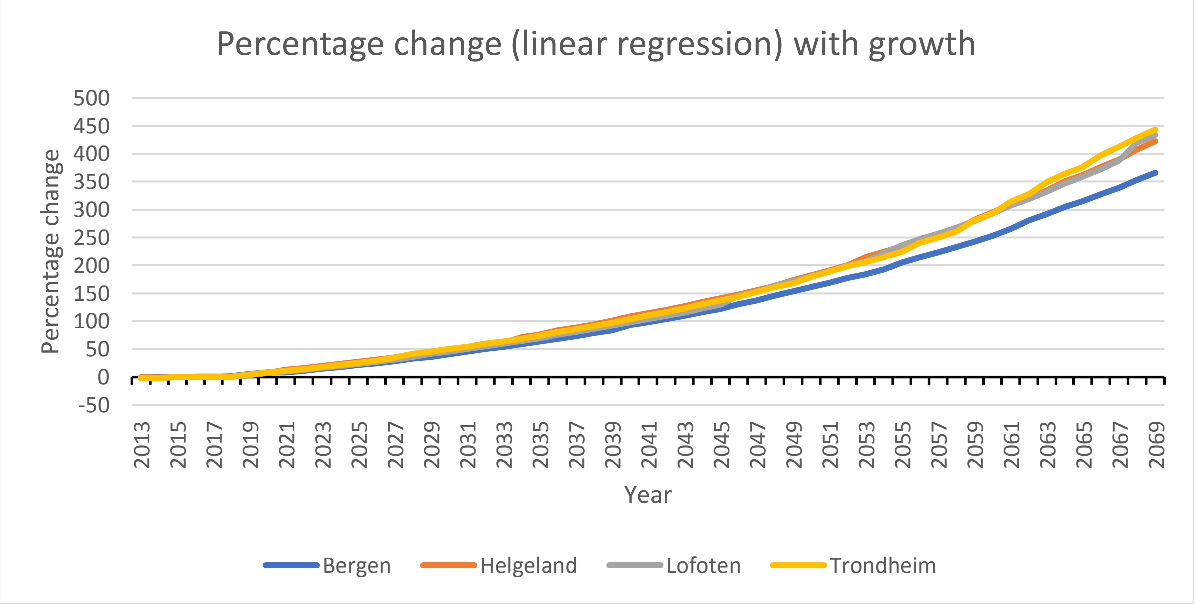

Figure 10- Percentage change in infection pressure with monthly linear regression for the temperature, taking into account growth from 2019 and onwards.

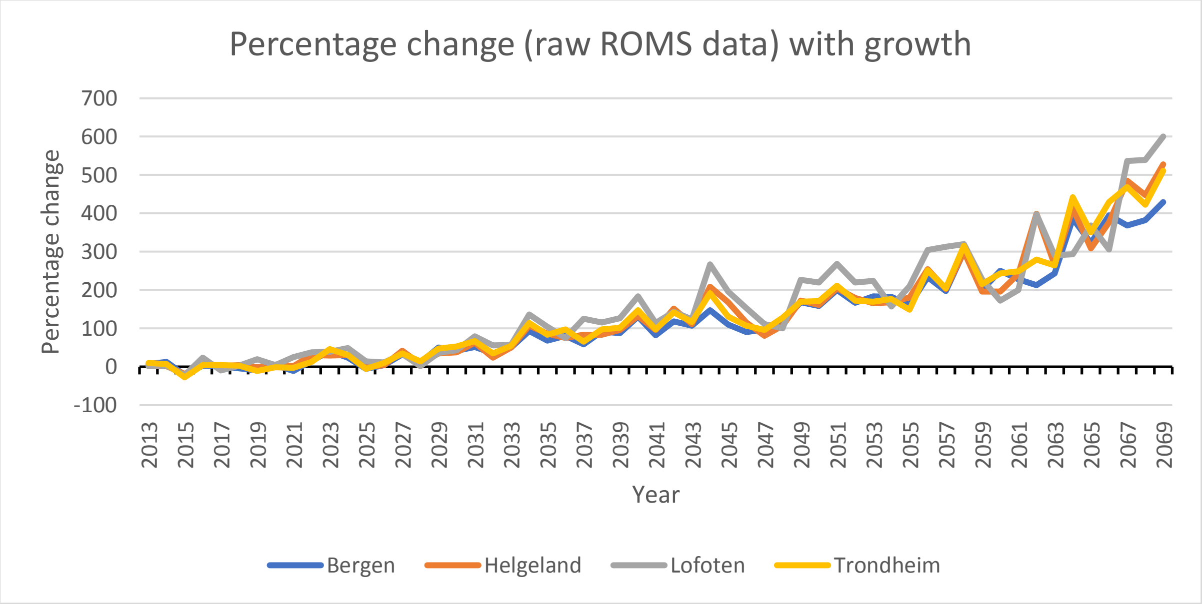

Figure 11- Percentage change in infection pressure over time given raw ROMS temperature data, taking into account growth from 2019 and onwards.

At this point we notice something interesting in Figure 11: Though the raw temperature data still gives us a more jagged line, the sheer force of the growth is starting to smooth out the differences. The second thing to be noticed is the sheer enormity of the growth. Of course, there will be an intervention long before the situation gets this dire (for reasons discussed in depth in chapter 6). Even without that it is entirely possible there are natural factors that will restrict the growth of infection pressure, though this is beyond the scope of this thesis.

However, if we make the assumptions stated beforehand then this is the result our model produces. At the very least this suggests that there are serious issues with simply maintaining the current density of aquaculture localities and then raising their biomass. Though this will be reviewed further later on in the thesis.

5.4. How is the growth in infection pressure distributed over the year?

At this point it seems logical to ask how the additional infection pressure is distributed over the year. We chose the Lofoten VAL to illustrate, as it has the greatest percentile increase of any of the locations, and the changes are therefore easy to see. However, the other VALs follow the same rough pattern. The years 2024, 2034, 2044, 2056, and 2069 were picked because they have unusually high spikes in percentage change (see Figure 7).

What we are doing here (in Figure 12) is showing the raw numbers for EIP (that is the actual number of infectious copepodites affecting the locality marked in the centre of the VAL).

Initially we are using the linear regression temperature data, which we would expect to be less extreme.

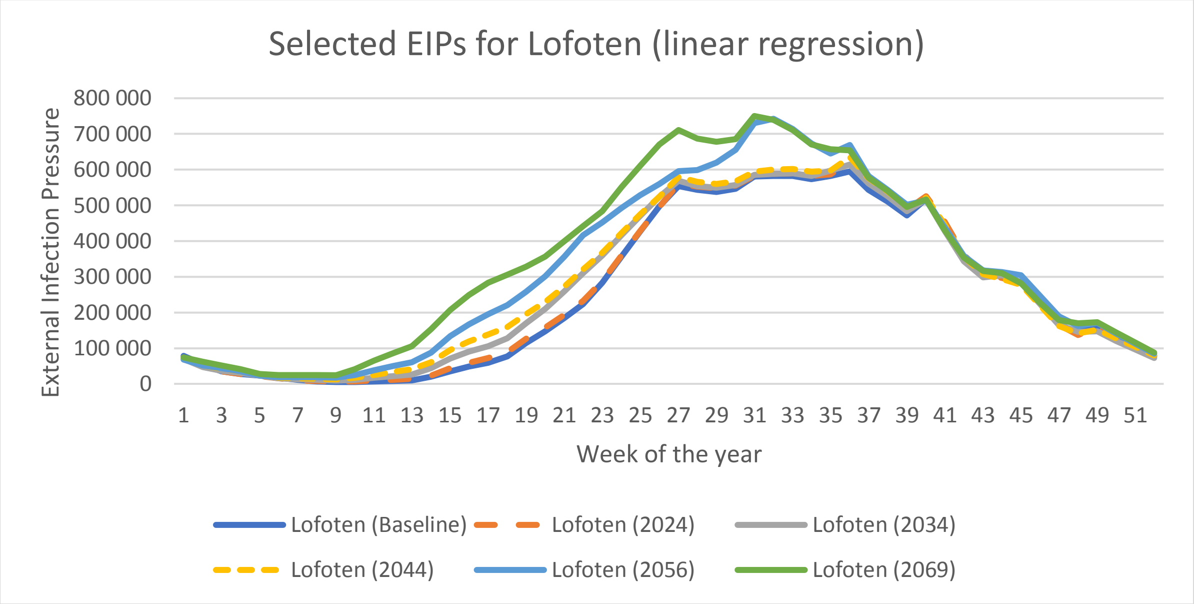

Figure 12 – Selected EIPs for Lofoten (linear regression). This graph shows the EIP (presence of infectious copepodites in the locality) based pm average of 2013-2018 (Baseline), and for the years 2024, 2034, 2044, 2056 and 2069.

In Figure 12 we note that the rise in infection pressure is slowly creeping upwards in the early part of the year, but that towards the last few months of the year infection pressure for all the different years is almost the same.

Now we turn to the same simulation, but using the raw temperature data from the ROMS model, as we can see the result in Figure 13 is very different:

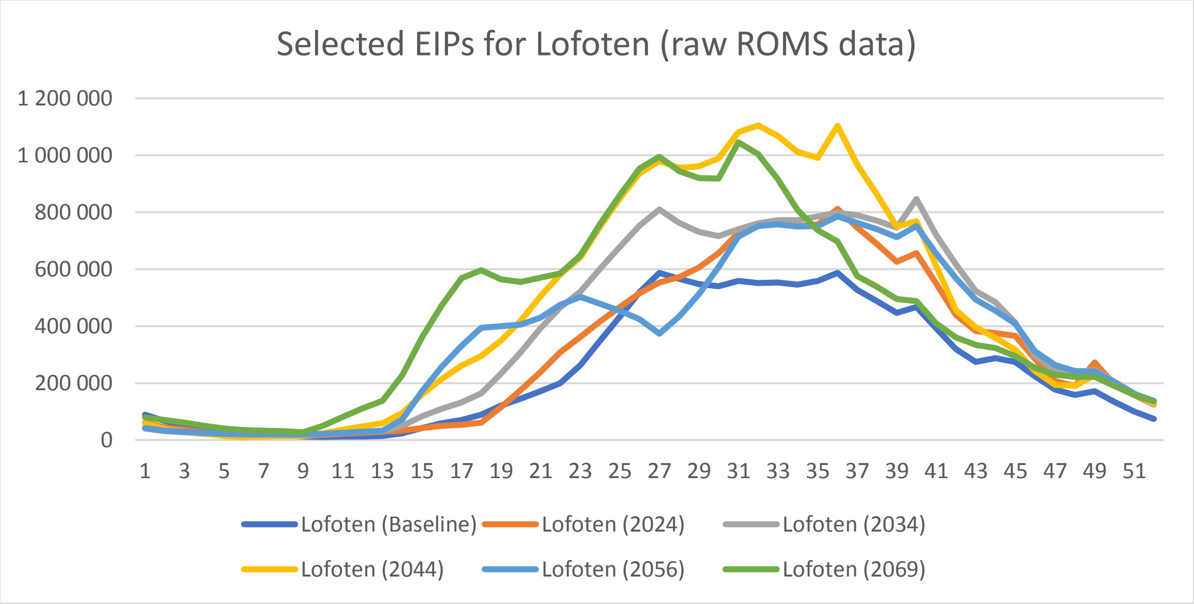

Figure 13 – Selected EIPs for Lofoten (raw ROMS data). This graph shows the EIP (presence of infectious copepodites in the locality) based pm average of 2013-2018 (Baseline), and for the years 2024, 2034, 2044, 2056 and 2069.

Figure 13 has the same tendency as in Figure 12, that is infection pressure is roughly the same in the beginning and end of each year, but in the middle of the year it spikes up. However, in this graph we see far more extreme results, both more chaotic and reaching much higher levels.

The mere fact of the rise in infection pressure in the early year could be quite important as smolt migration into the sea is greatly affected by temperature, but in Norway it currently occurs around April-August, depending on where in the country you are (Otero et al., 2014). So, will the earlier migration make up for the increased infection pressure in what is now the prime migration period? That is beyond the scope of this thesis, but it is potentially worrying, and worth future investigation.

5.5. How does monthly average temperatures change over time?

Why then do we have this increase in infection pressure early in the year? Looking at our linear regression data of temperature, it seems that climate change is making the winter months heat up much faster than summer months.

In Figure 14 (below) we have plotted the $\beta_{m,i}$, or average annual change in temperature of month m for VAL i (see section 4.4.4), which demonstrates this quite well:

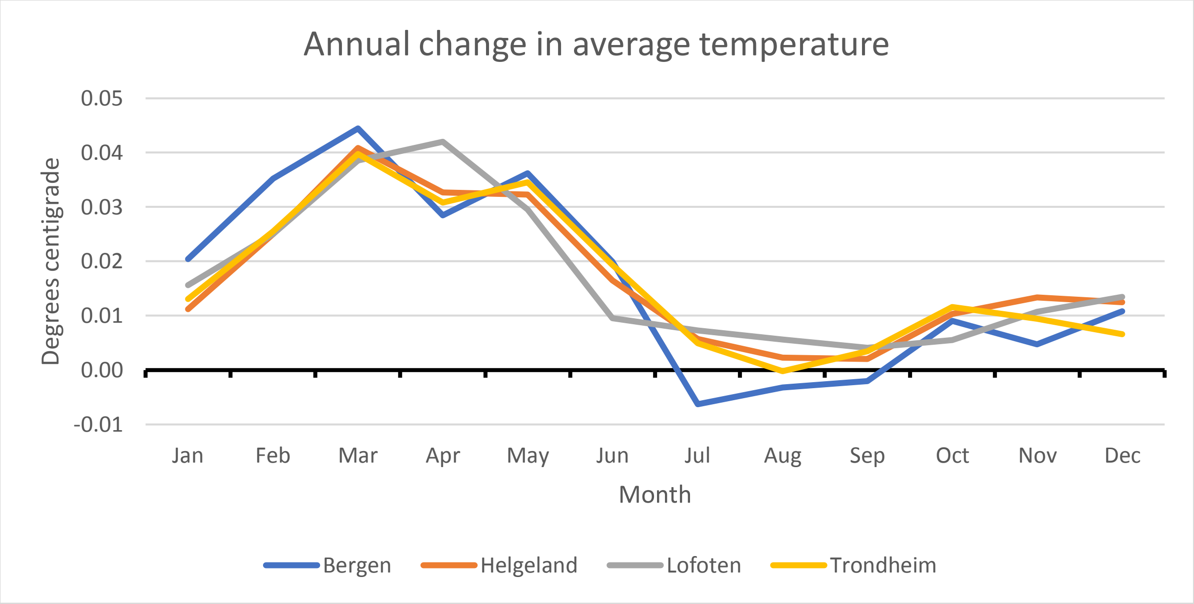

Figure 14 – Annual change in average monthly temperature over the period 2013-2069

5.6. How does changes in the yearly climate pattern affect salmon lice?

The importance of the previous section is perhaps best explained by showing a graph that overlays a graph of the ratio of adult female salmon lice to salmon, with another graph of the annual temperature change for each month (for the Bergen VAL).

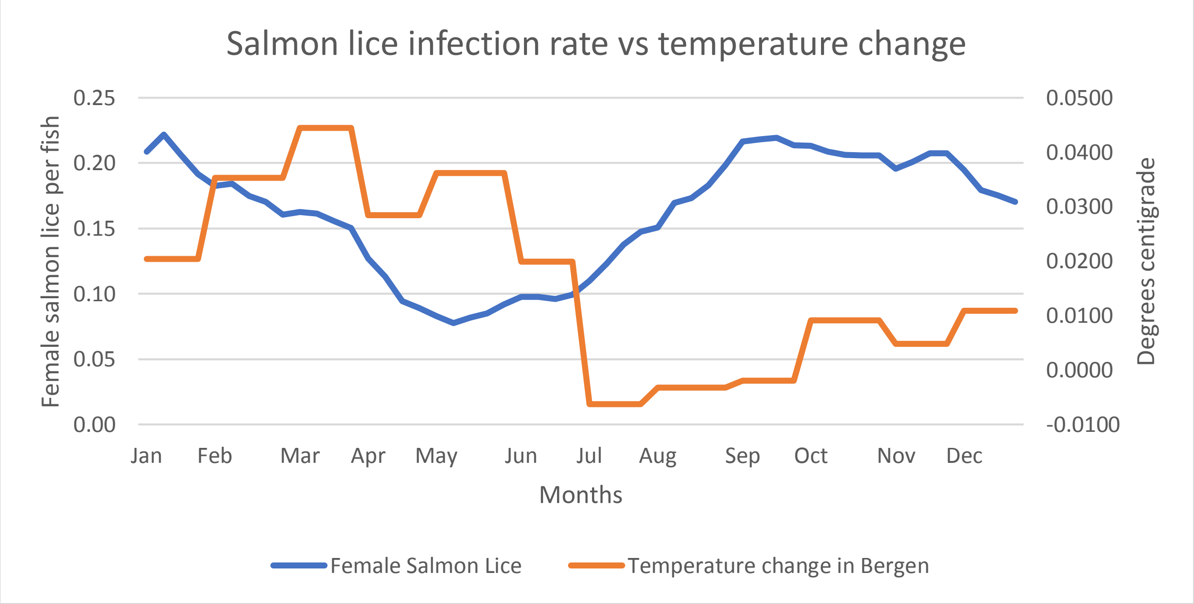

Figure 15 – Weekly female salmon lice per fish (average nation-wide for period 2013-2018) vs annual temperature change for each month (linear regression over the period 2013-2069)

From Figure 15 we see that the highest monthly temperature changes arrive during the point of lowest infestation. However, due to this being the wild smolt migration period (Revie et al., 2009), Norwegian law does enforce stricter limits on female salmon lice in this period (Nærings- og fiskeridepartementet, 2012). Since our salmon lice data from Barentswatch (2019) only goes back to 2012, we cannot be entirely certain to what degree this dip is due to effects from regulations, or to the life cycle of the salmon lice.

But as we know the salmon lice favours warmer temperatures (Revie et al., 2009; Samsing et al., 2016), something which is also assumed by our model (Kristoffersen et al., 2014) and demonstrated by the results of our simulation. This suggests that over time the infection rate would get worse in the January-June period, to match the slowly increasing monthly average temperatures. Which again suggests that our results may be overly cautious and conservative.

5.7. How does changes in the yearly climate pattern affect salmon lice?

Several studies are concerned with how increasing annual temperature amplitude (difference between warmest month of the year and the coldest) will affect salmon aquaculture (Hermansen & Heen, 2012; Lorentzen, 2008). We have therefore conducted an analysis of the development of the hottest and coldest months of the year, and the difference in temperature between them.

Our method was as follows: For each the VALs we went through the raw temperature data from the ROMS model and extracted the coldest (minimum) and warmest (maximum) month if each year. We then conducted linear regression to see how the temperatures of the coldest and warmest months of each VAL would change annually.

As in section 4.4.4, equation (15), we have: $T = \alpha + \beta(Y - 2013)$

Where T is temperature, α is the starting point, and β is the annual rate of change (positive or negative). See Table 2 for the values in different VALs.

Table 2 – Minimum is the coldest month; maximum the warmest month; and amplitude shows the temperature amplitude of the year. Place names are for Virtual Area Locations. α is the starting temperature, and β is the annual rate of change.

	Minimum		Maximum		Amplitude	
	α	β	α	β	α	β
Bergen	5.5512	0.0199	13.7484	0.0150	8.1972	-0.0048
Trondheim	5.3557	0.0119	12.3575	0.0210	7.0019	0.0091
Helgeland	3.8408	0.0103	11.5934	0.0193	7.7527	0.0090
Lofoten	3.4400	0.0195	10.4054	0.0136	6.9654	-0.0059

As we can see from Table 2 the results are somewhat inconclusive. Amplitude increases for Trondheim and Helgeland, but decreases for Bergen and Lofoten. We do however see that both the coldest and warmest months of the year will continue to become warmer in all four of our locations.

5.8. How does distance affect External Infection Pressure?

We now refer back to section 4.1 and equation (6), where we have that RR_{ij} is "The relative risk for infective copepodids produced at farm *j* to contribute to infection pressure at location *i*." (Kristoffersen et al., 2014). So, let us graph (in Figure 16) the value of RR_{ij} as a function of distance between localities *i* and *j*:

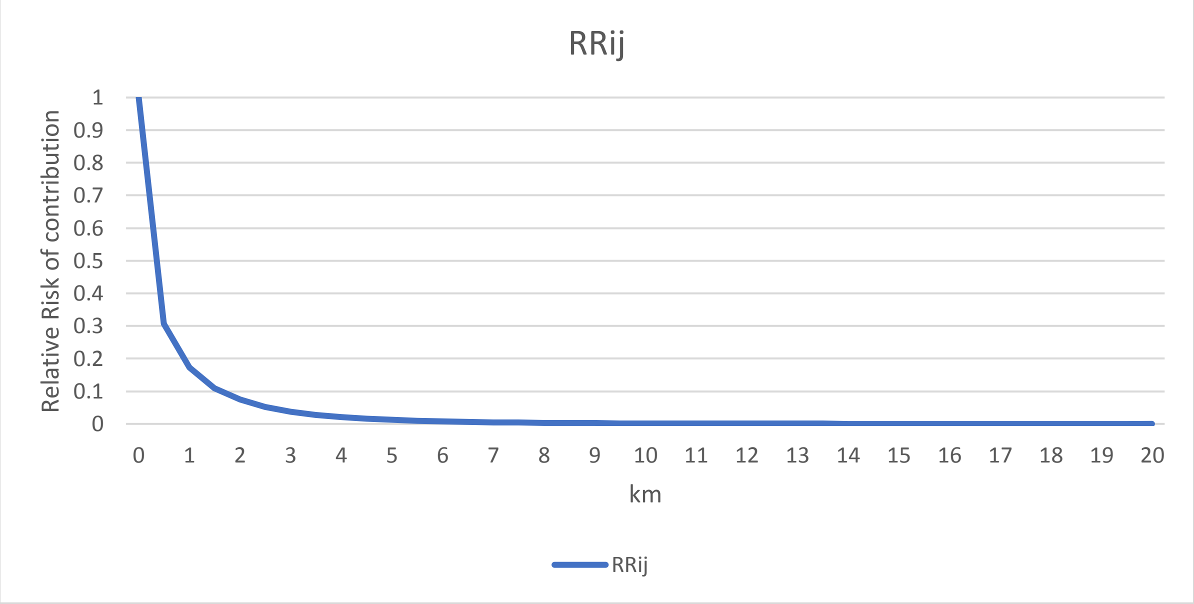

Figure 16 - RR_{ij} being the relative risk of a copepodite at locality j contributing to the infection pressure at locality j.

Figure 16 shows that RR_{ij} resembles an asymptotic function, except that for 0 km distance it equals 1. This strongly indicates that distance is a very important aspect to the risk of infection caused by a salmon fish farm.

5.9. Changing the Virtual Area to further explore the effects of distance

In order to quantify this effect, we have picked the Bergen VAL as our comparison and begun to manipulate the virtual area it is located in (see section 4.4.6). For this simulation we are assuming a growth scenario (see section 4.4.5).

We shall consider four scenarios:

1. Standard: The basic VAL as shown in Figure 4 of section 4.2.
2. Scenario I: We take the basic VAL and remove all the localities past the 20 km mark.
3. Scenario II: We take Scenario I and move all the localities at the 5 km circle to the 10 km circle.
4. Scenario III: We take Scenario II and move all the localities that are now at the 10 km circle to the 20 km circle.

These options are illustrated below in Figure 17:

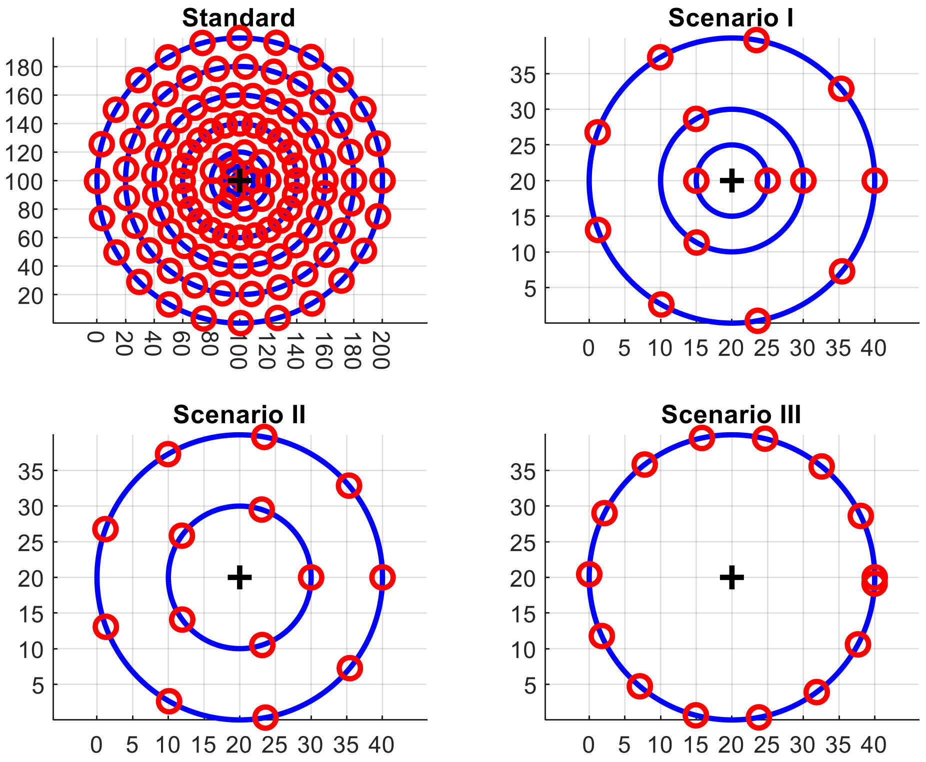

Figure 17 – All X and Y axis are in kilometres. Upper left corner: Standard scenario, all localities in their usual place; Upper right corner: Scenario I, all localities past 20km radius are removed; Lower left corner: Scenario II, as in (I) but all localities from 5 km away are moved to 10 km away; Lower right corner: Scenario III, as in (II), but all localities from 10 km away are moved to 20 km away.

Now we turn to the simulation, where all the scenarios (including standard) are plotted against each other (Figure 18):

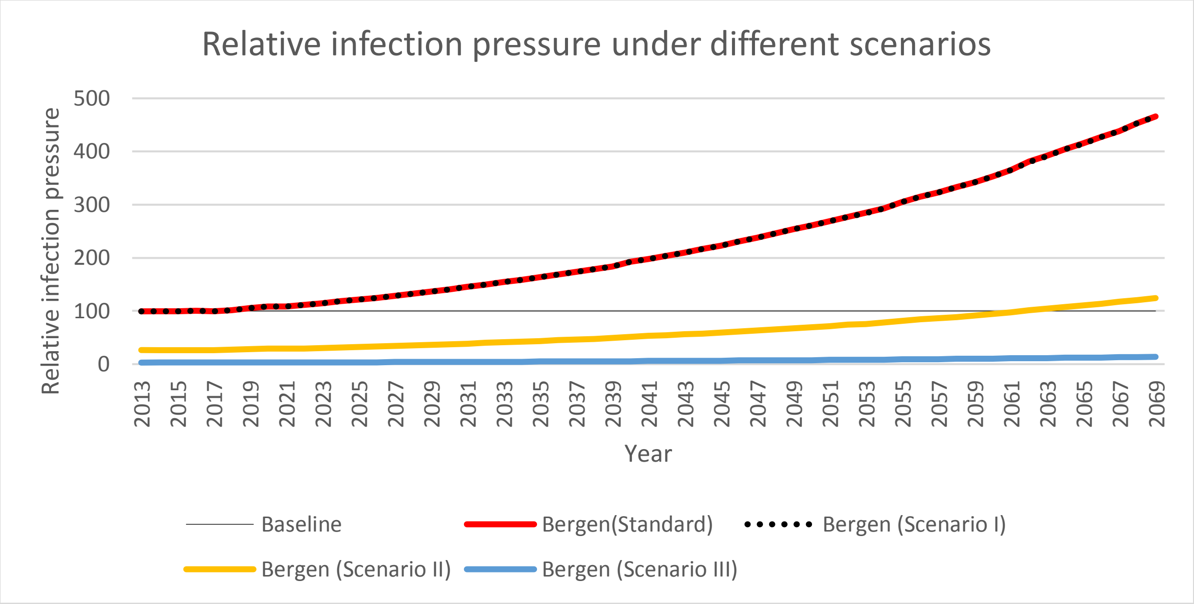

Figure 18 – Relative infection pressure using the Bergen. Baseline is what you would expect if the average of the period 2013-2018 remained inchanged; Standard is the normal growth scenario with linear regression for temperature; Scenarios I, II and III has various manipulations done to the virtual area as detailed above.

In Figure 18 show scenario I as a dotted line to be able to tell it and the standard scenario apart, suggesting that distant localities contribute almost nothing to the infection pressure. Likewise moving the remaining localities further out as with Scenario II and Scenario III leads to increasingly large drops in EIP. We point out that that there is no change in total biomass between scenario I, II and III. In other words: purely by adding distance between facilities we have massively cut the infection pressure.

Even with our anticipated growth it is not before 2062 that Scenario II reaches the same level of infection pressure as Bergen had on average in the 2013-2018 period. This suggests that firewalls (areas free of fish farms) would indeed be quite effective at reducing the spread of salmon lice. Under the heading firewall we include both the national salmon fjords (important fjords through which wild salmon migrate, which is kept clear of aquaculture facilities) (Serra-Llinares et al., 2014) and other natural obstacles, such as sheer water distance, between the localities (Tiller et al., 2012).

There is the potential for this to have regulatory consequences, which we will discuss in some detail in section 6.7.4.

5.10. Unexplained and surprising spikes in infection pressure

There is a popular simile as to the difference between weather and climate: Imagine a man with a dog on a leash, the dog runs up and down on the path quite randomly, while the man is walking slowly in a straight line. Though the exact position of the dog at any one time can be impossible to predict, the tendency, the direction of the man, can be told. The ROMS model is then, as mentioned in Chapter 5, quite reliable on a decadal scale (Lien et al., 2006; Travers-Trolet et al., 2018), but though we can make decadal forecasts, the weather in each year can still be quite unpredictable (Slingo & Palmer, 2011).

The relevance of this is very clear if you look at Figure 7 from section 5.1, we see a very noticeable spike in 2034, after a long period of fairly normal variation. Yet, even that only tells half the story, if you look at a week by week graph (Figure 19) of percentage EIP changes you find something even stranger.

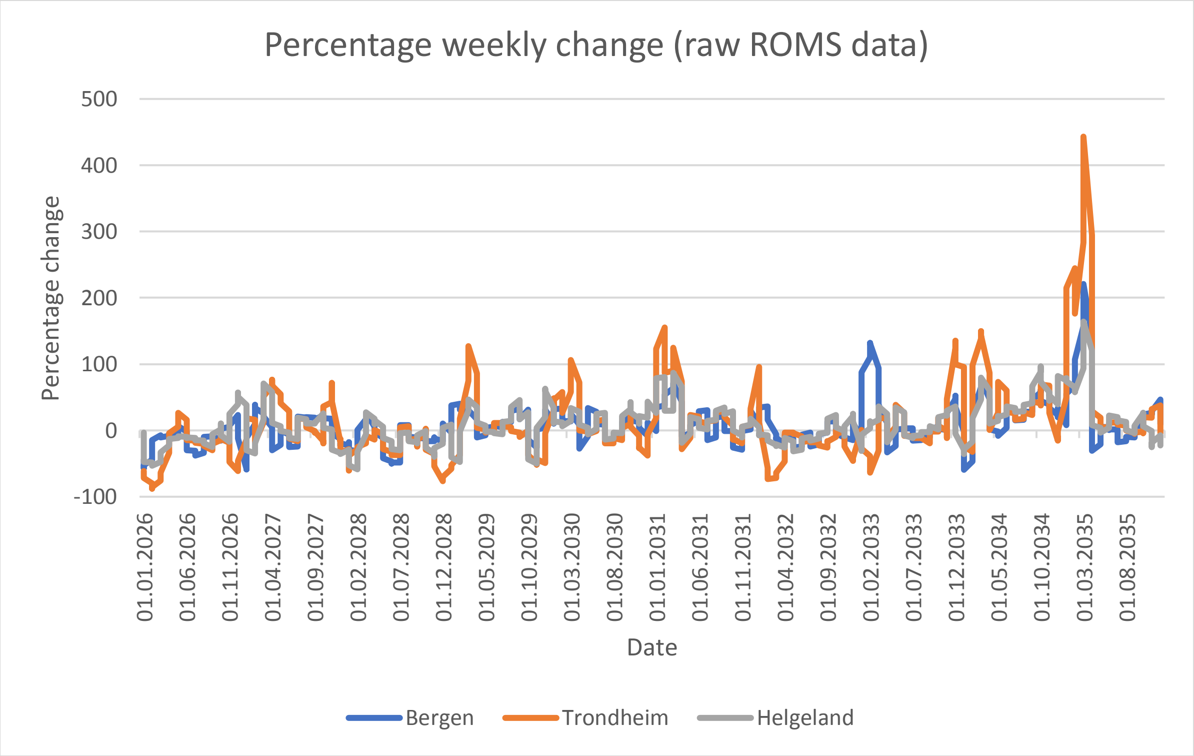

Figure 19 – Percentage change on a weekly basis from January 2026 to Decenber 2035. Lofoten VAL has been removed from this graph as its values were so extreme that they concealed those of the other VALs.

Looking at Figure 19 we see that after returning to norm at the end of 2034, there is a massive spike early on in 2035 in the February-early April period before returning to a fairly low level. Investigating the actual infection pressure data does not provide anything so graphically stunning, but it does show some very peculiar developments early in 2035 where infection pressures not only rise higher than normal but stay high for longer.

In the following decades (Figure 20) spikes like this become more and more extreme, and more and more common.

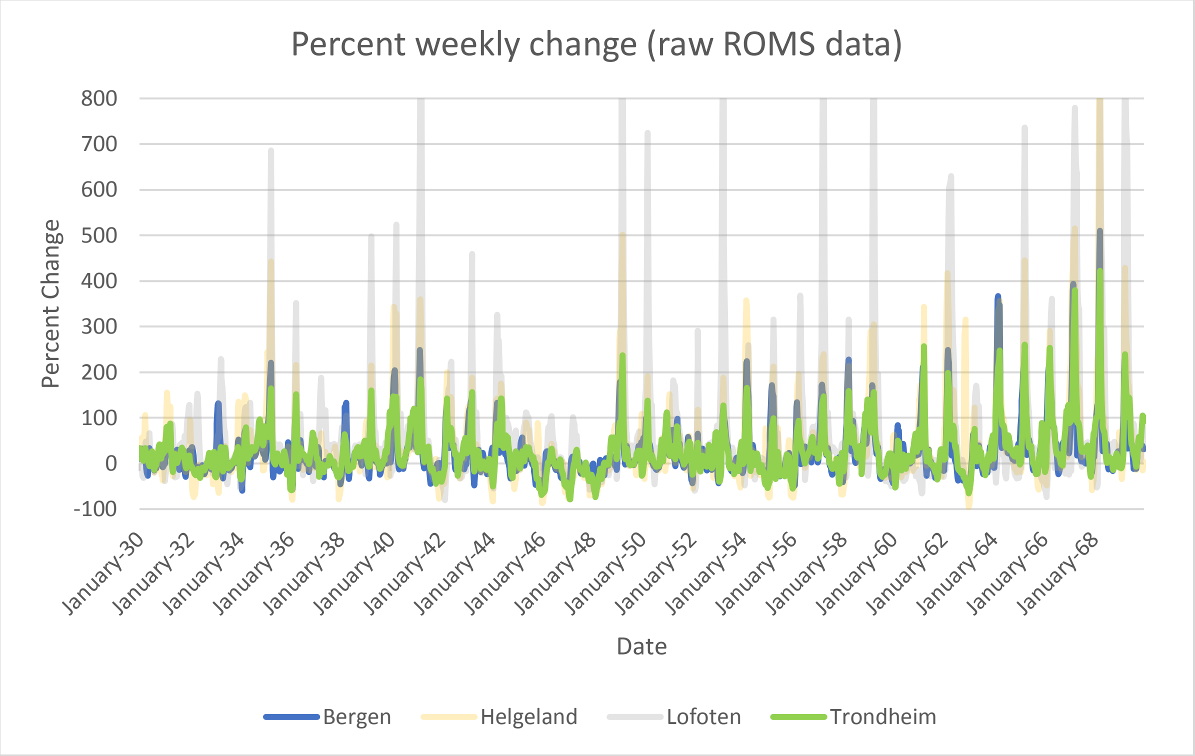

Figure 20—Percent weekly change from 2030 to 2069, note that Helgeland and Lofoten VALs have been made semi-transparent because their values were so extreme that they obscured the other graphs.

Yet even Figure 20 does not give us the whole picture, let us track a graph (Figure 21) of the rate of adult female salmon lice to each salmon, against a graph (Figure 21) showing the total infection pressure (amount of infectious copepodites) for both the baseline year and 2035. We are using the Trondheim VAL for this since it is representative of the rest.

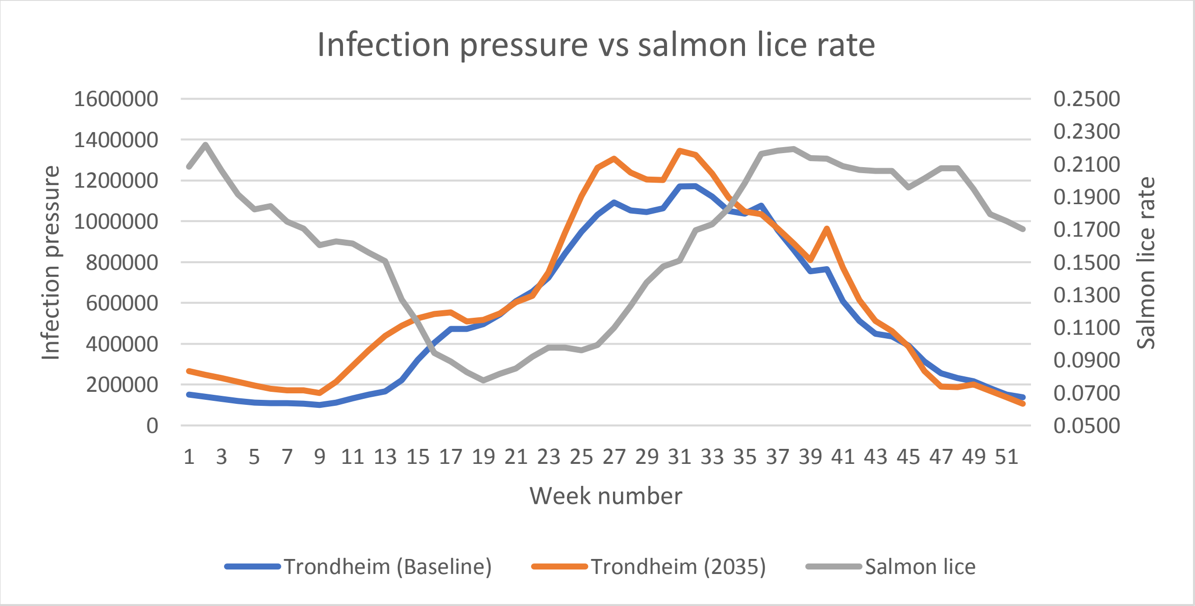

Figure 21—Infection pressure vs salmon lice rate. This is actual raw number for infection pressure instead of comparative.

From Figure 21 can see the salmon lice infection ratio reaches its nadir in week 19, which is also when the infection pressure for 2035 does so. In short, the infection pressure, being dependent on the salmon lice number, slows its growth in response to the declining infection ratio. However, we know that infection rate and infection pressure are linked both ways (Aldrin et al., 2017; Jansen et al., 2012), but in our case we kept the weekly infection rate as a constant.

However, when we performed a test where we doubled the infection rate in the period week 9 to week 23 (slightly exceeding the time period where salmon lice are required to be under 0.2 (Nærings- og fiskeridepartementet, 2012)) we found that it made very little difference to the nadir of the infection pressure. Apparently, the ocean temperatures overpowered the effect of the infection ratio.

This shows some of the uncertainty about our model and questions the validity of some of our assessments, mostly in that we may have been too conservative about potential impact. What would be the consequences of the development we described? For this we have not found any data whatsoever. Nor have we found any sources suggesting that something like this has happened before.

6. Discussion

In this chapter we discuss how the results from chapter 5 will affect both wild and farmed salmon, as well as the industries and other stakeholders who rely on them. We will touch on both purely physical impacts on the salmon populations (wild and farmed), but also on economics knock-on effects. The latter will include discussions of real-estate prices as well as a look at how the wider community is affected. Since we will touch on a great many different areas, we will also present some relevant theory in this chapter, rather than have the theory set aside as a separate chapter.

6.1. Direct impact on wild salmon

6.1.1. General impact

What is the effect of salmon lice from aquaculture on wild salmon? Studies from Scotland and Ireland show that the construction of salmon aquaculture facilities coincided with reduced fishing in nearby rivers (Shephard, MacIntyre, & Gargan, 2016). In Norway government sponsored reports indicate that salmon lice from aquaculture facilities is not just a threat to farmed salmon, but also increases the mortality rates of wild salmon (Grefsrud et al., 2018). So, although there may be some uncertainties around the precise influence of salmon lice on wild salmon (Karlsen et al., 2016), there seems to be a consensus for salmon lice from farmed salmon having a detrimental effect on wild salmon (Grefsrud et al., 2018; Kristoffersen et al., 2018; Olaussen et al., 2015; Revie et al., 2009). Further several of these studies suggest that measuring infection pressure gives a good indication of the threat to the wild salmon population (Grefsrud et al., 2018; Kristoffersen et al., 2014; Revie et al., 2009). This is borne out by studies on trout, which show that infection pressure (from farms within 30 kilometres) can explain 41% of the abundance of sea-lice on wild fish (Serra-Llinares et al., 2014).

Although wild salmon suffer from many of the same problems as farmed salmon, there are a few important caveats. A wild salmon spends its early years living in fresh water (a river) where it is not in any danger whatsoever from salmon lice, before at a certain stage the immature salmon (called smolt) leaves its river and migrates to the sea (Grefsrud et al., 2018),

As is shown in Karlsen et al. (2016) we are not entirely certain of how the out-migrating smolt travels after leaving its rivers, there is evidence to indicate some smolts may go into the fjord system for a time before leaving. Likewise, it can move across the width of the fjord, or when it reaches the islands at the mouth of many fjords it might enter the sound between the island and the mainland, or even end up in another fjord (Karlsen et al., 2016).

Previous studies document that there are often areas of intense infection pressure on the route between the river and the sea, where the smolt runs the risk of infestation (Olaussen et al., 2015; Revie et al., 2009). Restrictions on the ratio of adult female salmon lice to salmons does not fully compensate, as the large numbers of salmons in the fish farms means that an intense infection pressure can still arise (Revie et al., 2009). This can apply even to protected fjords and rivers, if the protected area is too small, or there is a fish-farm within 30 kilometres (Serra-Llinares et al., 2014)

We have already seen that the infection pressure is going to increase, which means that there will be an increased number of infections on the wild salmons that passes by fish-farms (Serra-Llinares et al., 2014). Not only that, but, as mentioned in section 6.2, these salmon lice will mature faster than before (Stien et al., 2005) even as they infest the salmon at the most vulnerable stage of its sea-faring life (Olaussen et al., 2015).

Quantifying what effect this will have is tricky, especially given the way that the traffic light system is set up to mitigate this, by defining green light, yellow light and red light in terms of how many wild salmon are likely to be killed (Karlsen et al., 2016). This system can easily be illustrated as in the table below (note here population refers to wild salmon population):

Table 3 – Translated from Karlsen et al. (2016)

Low risk / influence	Moderate risk / influence	High risk / influence
It is likely that < 10 percent of the population will die due to salmon lice infection.	It is likely that 10-30 percent of the population will die due to salmon lice infection.	It is likely that > 30 percent of the population will die due to salmon lice infection.

The system is new, so it is not clear how it will deal with, say, sudden temperature fluctuations that temporarily push a yellow zone up into the red zone. Though overall a general increase in mortality of wild salmon as a result of increased infection pressure does seem very probable (Kristoffersen et al., 2018; Serra-Llinares et al., 2014).

Despite the term traffic-light system red does not necessarily mean stop, since you can still apply for a permit to expand in the red zones (Fiskeridirektoratet, 2018) and for now there will be no production reduction in the red zones (Nærings- og fiskeridepartementet, 2017). This of course has caused some public debate with environmentalist organisations objecting (Woie, 2018), which folds into the trend discussed in 6.7.3 of public debate.

6.1.2. Impact on the seaward migration time of the wild smolts

There are many reasonably accurate models as to when the salmon will leave its river (Karlsen et al., 2016; Otero et al., 2014), and it seems clear that salmon will begin to migrate earlier if the temperature increases (Otero et al., 2014; Travers-Trolet et al., 2018).

Looking at Figure 12 and Figure 13 we see what looks like a graph that is gradually moved to the left. Meaning that the annual rise in infection pressure keeps starting earlier and earlier. However, if the smolts begin migrating earlier they might get ahead of this development, or an earlier migration might partly compensate for the earlier rise in infection pressure.

The work of Otero et al. (2014) states that the current tendency is for the smolts to descend to the sea 2.5 days earlier each decade. They also have a very detailed model for simulating the migratory behaviour of the smolts, but modelling this is beyond the scope of this thesis (though very much a topic that requires further research). Instead we will illustrate the issue with a very rough estimate:

Using available data from Otero et al. (2014)on when the smolts have made 25% descent (that is when 25% of the smolts who are going to migrate this year have done so) we look at the average migration times for the rivers within 2° latitude of our locality and average them out into week numbers. Again, we repeat that this is a quite rough estimate, but it gives us week 18 for the Bergen VAL; week 19 for the Trondheim VAL; week 21 for the Helgeland VAL; and week 23 for the Lofoten VAL.

We will now assume two scenarios:

1. The wild smolt migration continues to occur 2.5 days earlier each decade.
2. The sild smolt migration begins to occur 7 days earlier each decade.

We then initially (for Figure 22 and Figure 23) assume that this is a linear-regression (see section 4.4.4) steady-state scenario (see section 4.4.5), since growth is likely to overpower any benefit from an earlier migration. But for Figure 24 we will assume a normal growth scenario.

Our comparison will be done thus:

$$(16)\%Change_{Y,i} = \frac{EIP_{w*,Y,i} - EIP_{w,baseline,i}}{EIP_{w,baseline,i}} \cdot 100$$

$\%Change_{Y,i}$ is percentage change (as in equation (13) section 4.4.2).

$EIP_{w*,Y}$ (External Infection Pressure [EIP] for week w*, year Y and VAL i)

$EIP_{w,baseline}$ (EIP for the baseline for week w for VAL i)

However, w is the week when the salmon would migrate now, but w* is the week when the salmon would migrate in the future (either 2.5 days or 7 days earlier per decade). Thus, we are comparing EIP at the week the salmon would go in the baseline year, against the EIP in the earlier week in the simulated year.

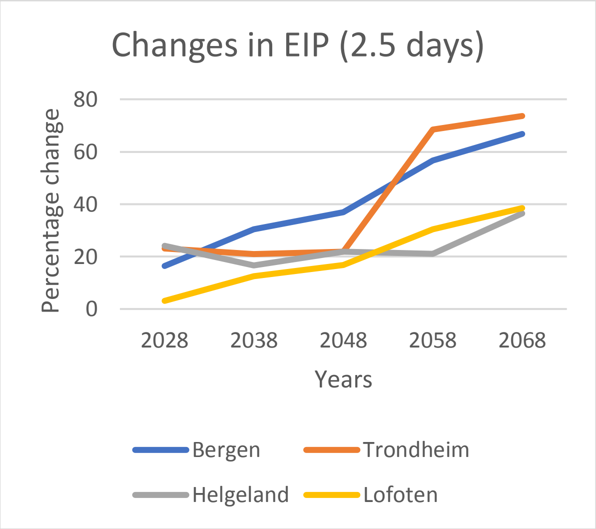

Figure 22—Changes in External Infection Pressure affecting migrating smolts if we assume the migration starts 2.5 days earlier each decade.)

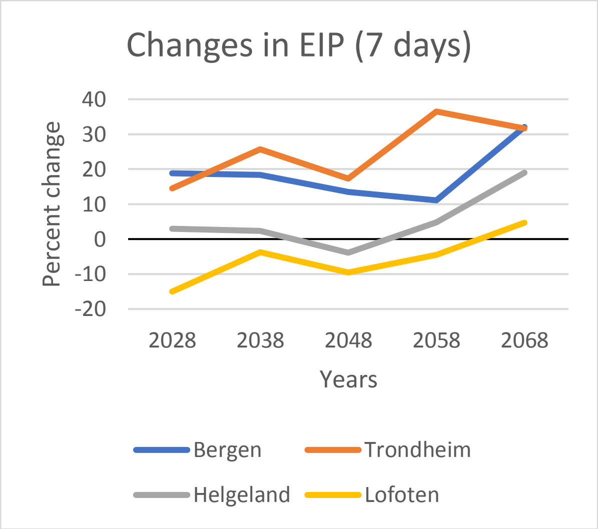

Figure 23—Changes in External Infection Pressure affecting migrating smolts if we assume the migration starts 2.5 days earlier each decade.)

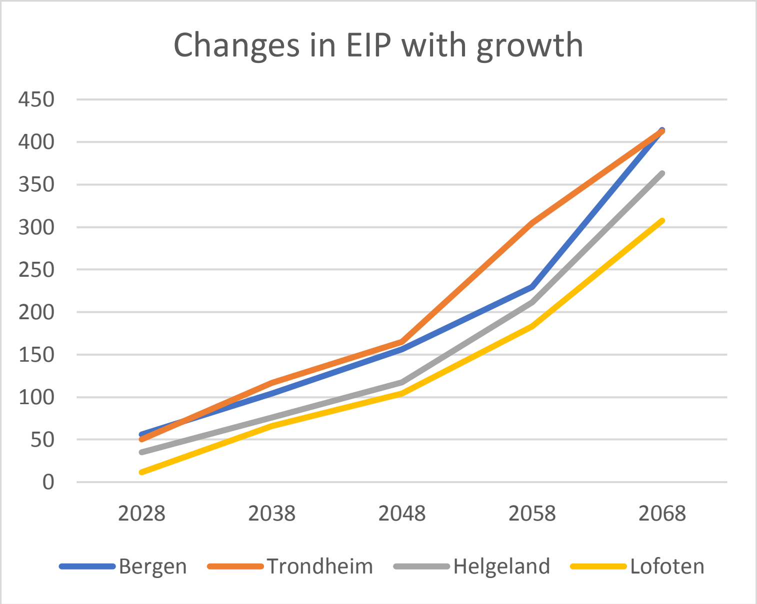

Figure 24—Changes in External Infection Pressure affecting migrating smolts if we assume the migration starts 7 days earlier each decade.), and that fish stocks are growing.

We should again point out that these are very crude estimates, warranting further examination. In particular having the migration of smolts occur 7 days earlier each decade is exceedingly unlikely (the rate of previous ocean heating mentioned in Otero et al. (2014) is mostly in line with what we see in our projections, and therefore we expect the trend of 2.5 days earlier migration a decade to continue). Even in the extreme 7-days earlier migration per decade scenario we see that trends will continue to worsen in the Bergen and Trondheim locations. But assuming no growth in the industry, earlier migration may help offset some of the negative effects of the increased infection pressure. If we a growth scenario (see section 4.4.5), then even with migration times happening 7 days earlier each decade the effect of the growth overpowers that of the earlier migration.

Our conclusion is that the increased infection pressure will indeed have a detrimental effect on wild salmons, and it seems unlikely this effect will be fully compensated for by earlier migration times.

As a quick note regarding section 5.10, as we discussed the "spikes" documented there tend to go back down by the time you come near the smolt out-migration. However, it cannot be ruled out that the very earliest migrating smolts may be affected by such a "spike", but we cannot be sure of this or of the effect this might have. This is definitely an area where further studies are warranted.

6.2. Direct impact on nearby salmon fish-farms

Infection pressure is, as we have argued elsewhere, a good predictor of how likely a locality is to develop an infection, increased production pressure means an increased risk of an infection (Kristoffersen et al., 2014). As we can see in Chapter 5 (see Figure 6 to Figure 13, and Figure 18 to Figure 20) all of our scenarios and variations predict that, over time, the infection pressure will increase, thus increasing the chance of neighbouring localities being infected.

However, the problem is further complicated, for the entire life cycle of the salmon lice is temperature dependent (Samsing et al., 2016; Stien et al., 2005). Interestingly, with increased temperatures the survival rates increase and development times decrease in the stages between infective copepodites, mobile salmon lice, and adult salmon lice (Stien et al., 2005). For a graph of the decrease in development time from egg to adult see Figure 1, but it is also interesting to look at decrease in time from egg to infectious copepodite (Figure 25) and from infectious copepodite to mobile adult (Figure 26).

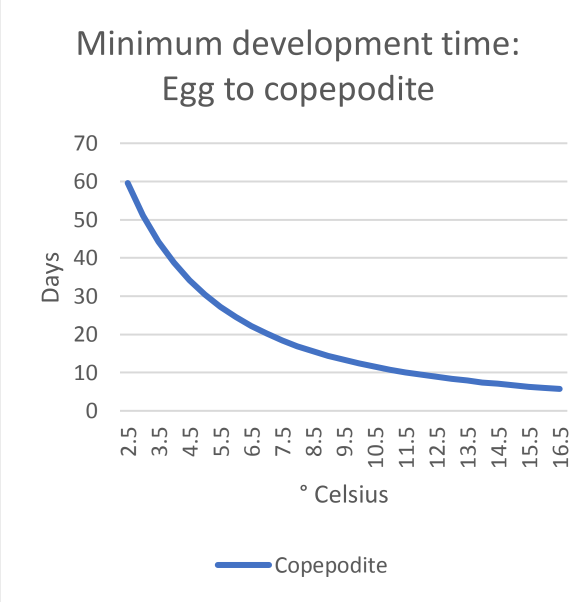

Figure 25—This graph shows how many days it takes to go from laid egg to infectious copepodite. Development times given temperature comes from Stien et al. (2005).

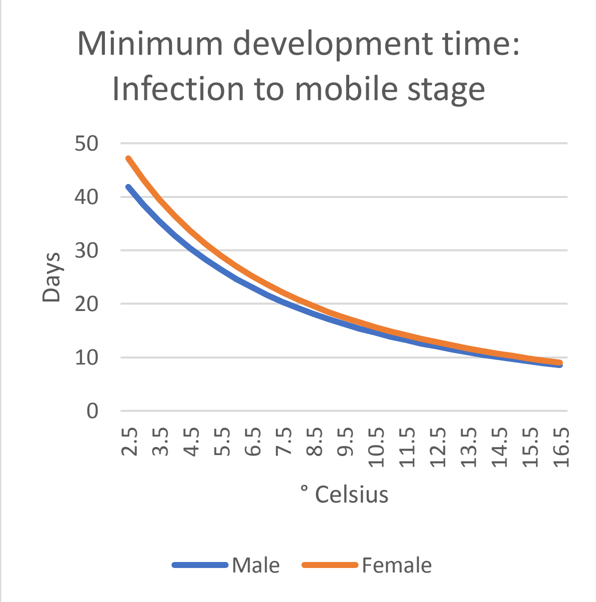

Figure 26—This graph shows how many days it takes to go from infectious copepodite (that has succeeded in infecting a host) to the mobile stage. Development times given temperature comes from Stien et al. (2005).

Once you have a local population of adult females these will of course also contribute to the infection pressure, and their proximity to each other exacerbates the problem (Kristoffersen et al., 2014)(Also see Figure 16).

In plain language: The warmer the seawater the greater the risk of infection, and the faster an infection will go from copepodites to reproducing adults.

The situation is made worse by the fact that the natural life-cycle of the salmon lice (Rittenhouse et al., 2016) may be affected by the way that the monthly temperatures are changing (Figure 15). Will this increase the infection rate in January-June? Given that salmon lice populations are also temperature dependent this seems probable (Aldrin et al., 2017). Such an increased infection rate (e.g. a greater abundance of adult females) will again further increase infection pressure (Kristoffersen et al., 2014) in the early months of the year.

All other things being equal we find it likely that the detrimental effects of the salmon lice problem will grow worse as temperatures rise. It should however be noted that the direct harm from sea-lice is likely to be limited, as enforced treatment means that farmed salmon rarely has an infection rate that would threaten the health of the fish (Revie et al., 2009).

6.3. Direct impact on aquaculture income

Salmon lice are already a major problem for salmon aquaculture (Grefsrud et al., 2018), but the issues we have raised both in the previous sections and in chapter 5, suggests that this problem will only get worse as time goes by.

In this section we will be discussing the direct economic losses caused to aquaculture by salmon lice. We will assume that regulations remain constant for the purpose of this section, as the various studies on the cost of salmon lice in Norway (Abolofia et al., 2017; Liu & Bjelland, 2014) only deal with current regulations. However, we believe more studies are needed on the likely effects of possible future regulatory regimes.

Costello (2009) provides a very good overview/summary of the issues (see Table 4)

Table 4 – A ranked importance of impacts of sea lice on the profitability of salmonid farming where control measures prevent pathogenicity [from Costello (2009)]

Rank	Impacts	Significance if sea lice control effective
1	Purchase costs of parasiticides Purchase and maintenance costs of equipment Staff time in research, management and control	17-30% (Mustafa, Rankaduwa, & Campbell, 2001; Rae, Mordue, & Pike, 2002) of total lice control costs
2	Reduced fish growth	5-15% smaller weight (Sinnott, 1998)(M.J. Costello, unpublished data)
3	Reduced food conversion efficiency	5% more feed required (Sinnott, 1998)
4	Reduced marketability because of disfigurement by lice	1% fish downgraded in Atlantic Canada (Mustafa et al., 2001) and up to 15% in Scotland (Michie, 2001)
5	Stress and accidental mortalities because of parasiticide treatments	Only significant for bath treatments and included in above costs.
6	Negative publicity from the use of parasiticides that may leave residues in fish fillets, and/or are released into the coastal environment Negative publicity and perhaps increased control requirement where farms may act as sources of sea lice that cause mass infestations (epizootics) that impact on wild fish populations of commercial, recreational, and/or cultural value	While an estimate could be derived from the price premium of organic salmon, such production is negligible globally
7	Losses because of secondary infections	No evidence for significant transmission of pathogens by sea lice, and if controlled, damage to host skin will be minimized
8	More expensive farming practises	Preventive measures also minimize transmission of other pathogens, so this is considered a cost of business
9	Fish mortality	< 1% (as non-pathogenic)

We will focus on ranks 1-2 for now, though in section 6.7.3 we will return to the issue of rank 6 regarding publicity.

From Revie et al. (2009) we have that low-levels of infestation are not likely to lead to direct mortality, but will tend to cause loss of appetite, lower growth rates, and, as is also confirmed by Costello (2009) may lead to the fish being downgraded at sale. Other studies also mention a reduced food conversion efficiency (e.g. how well food is converted into salmon biomass) (Costello, 2009; Mustafa et al., 2001). Additionally, we find elsewhere that chemical treatment is both costly in itself and in that it increases mortality and reduces growth (Liu & Bjelland, 2014).

From Liu and Bjelland (2014) we have that sources show that in Norway the cost of sea lice was 0.79 NOK per kg of salmon in 2011 (her source for this is no longer online), and Liu and Bjelland (2014) cited Jensen (2013) as stating the cost in 2013 had risen to 2.45 NOK per kg of salmon (later on Liu and Bjelland (2014) tested several treatment scenarios and one of them was quite close, 2.42 NOK/kg, to the quoted cost). This increase was attributed to an increase in sea lice infestation and therefore to treatment. We will however note that Costello (2009) cites a cost of 1.503 NOK/kg from 1997, and further Iversen, Hermansen, Nystøyl, and Hess (2017) cites costs slowly rising (with variation) from 0.20 NOK/kg in 2011 to 0.72 NOK/kg in 2015, only to rapidly decline to 0.40 NOK/kg in 2016.

There appears to be agreement about a general increase in treatment costs between 2011 and 2013 (Jensen, 2013; Liu & Bjelland, 2014), which continued to 2015 (Iversen et al., 2017). This, however, is where the agreement ends, and we see widely divergent costs for what is supposed to be the same thing measured at the same time. We hypothesise that, among other things, this is due to: the great difficulty in measuring the cost of salmon lice; disagreement over what should be measured; and potentially great fluctuations in the cost depending on infection pressure and other factors.

We have not seen anything to contradict Liu and Bjelland (2014) that increased incidents of sea lice increased costs of treatment, or Costello (2009) statement that as production increases so does sea lice control costs. This would be in line with Kristoffersen et al. (2014) showing that increase biomass (number of fishes) increases infection pressure, which tends to lead to more infections (Jansen et al., 2012).

We do however have an equation of a profit function from Abolofia et al. (2017), which we can use to illustrate the issue, unless specifically noted the explanations are from said article, with direct quotes in “-“:

$$(17)\ \Pi(T) = P(T) \cdot \left(B_0 + \int_0^T \dot{B}\left(t, L(t)\right) \cdot dt\right) \cdot e^{-rT} - C_f \int_0^T FCR \cdot B\big(t, L(t)\big)^{\cdot} \cdot e^{-rT} \cdot dt - C_r \sum_{n=1}^{N} e^{-rT_n}$$

$\dot{B}$ is farm biomass growth, which is a function of time *t* and *L(t)*

B_0 “is the initial lice-free stock of biomass”

$L(t)$ is the amount of lice per fish over a production cycle.

T “is harvest time.”

$P(T)$ is the price per kg of the fish at harvest time.

C_f “is the unit price of feed”

FCR “is the feed conversion rate (i.e., the per-period quantity of feed use per kg of biomass growth)”

r “is the farmer’s discount rate”

C_r “is the unit treatment cost”

N “is the total number of treatments”

T_n “is the time at which treatment n{1,N} occurs.”

(Abolofia et al., 2017)

One issue which Abolofia et al. (2017) does not fully delve into is that N, $\dot{B}$, and $L(t)$ are necessarily also temperature dependent variables.

To begin with N, we know that Norwegian regulations require fish-farms to begin treatment when a certain ratio of adult female lice to salmon is reached (Nærings- og fiskeridepartementet, 2012). As we pointed out in section 6.3 the increased temperatures may lead to more and faster developing infections. This means that more treatments may be required, so the number N, the number of treatments, is a function of temperature.

Secondly, we know that $L(t)$ is highly temperature dependent (see chapter 4 and chapter 5). However, $\dot{B}$ (farm biomass growth) is also temperature dependent as we can see from Hermansen and Heen (2012), Lorentzen and Hannesson (2006), and Lorentzen (2008) who all discusses the effects of global climate change (temperature increase) on the growth of farmed salmon.

So, will the increase in biomass growth make up for the increase in salmon lice? That is a valid question, since the increase salmon lice itself hampers biomass growth (Revie et al., 2009). And none of Hermansen and Heen (2012), Lorentzen and Hannesson (2006), or

Lorentzen (2008) all of whom documented that there would be greater growth, took into account the accompanying increase in salmon lice.

However, Abolofia et al. (2017) does take into account the effect of temperature on biomass growth, and the conclusion is that the marginal effect of additional salmon lice increases with higher temperatures. That is to say warmer temperatures cause salmon lice to do more harm, especially when dealing with younger uninfected fish (Abolofia et al., 2017). Which makes sense when you consider this also speeds up maturation (Stien et al., 2005), and that mobile salmon lice inflict far more damage than the immobile (Karlsen et al., 2016).

Therefore, we feel reasonably confident to conclude that increasing temperatures and salmon lice infection pressure will indeed lead to greater costs for the aquaculture industry. Overall profits may also increase, especially under more permissive license regimes (Hermansen & Heen, 2012), but it is very likely that the cost of treatment in NOK/kg of salmon produced will also increase.

Another issue is that salmon lice have the potential to cause downgrading (defined as some physical quality of the salmon which leads to it losing value somewhere in the value chain) due to eating the skin of the salmon, leaving unsightly lesions along the belly, ugly wounds (Michie, 2001), and being particularly damaging to the head region (Pike & Wadsworth, 1999), and thus lead to the salmon selling at a discount (Michie, 2001). Obviously faster maturation leading to more mobile salmon lice (see Figure 26) would tend to lead to more skin-damage, since this is the stage that is most harmful to the salmon (Revie et al., 2009).

Such downgrading is a serious problem in Scotland (Michie, 2001), and Norwegian regulations (§17 of the Regulation on the Quality of Fish and Seafood [Trans: ours], (Nærings- og fiskeridepartementet, 2013)) also requires that damaged salmon be sorted into a lower quality grade. In Norway there are three such quality grades: superior, ordinary, and production, with the latter not being permitted for export (Nærings- og fiskeridepartementet, 2013). According to Grieg Seafood (2017, 2018) downgraded salmon is discounted (from the price of superior grade) according to standard rates of deductions, with the deduction for ordinary grade being NOK 1.50-2.00 per kg GWT (gross weight tons), and for production grade being NOK5.00-15.00 per kg GWT. When we consider that production was 1.2 million tons in 2017 (Statistisk sentralbyrå, 2017) the scale of the potential problem is immediately obvious.

This is closely connected to section 5.10 where we show that our projections reveal strange "spikes" of greatly increased infection pressure in the February to late March region. We have from Michie (2001) that the damage and lesions caused by salmon lice in winter (February to April in particular) does more damage because the skin heals slower. This means that the sort of "spikes" seen in section 5.10 could increase the infection and damage caused in what is a particularly vulnerable period, and thus cause damage enough to have the affected salmon reduced in quality, leading to monetary loss.

6.4. Local economic value creation from recreational salmon angling

One issue in discussing recreational salmon angling as an important factor for local economies is the sheer varieties of type of land ownership ranging from private, to state, to municipal, and all of these can have different stipulations and regulations concerning their use (Andersen & Dervo, 2019). In addition the potential income varies, some areas, like Alta, can auction off a day or two of prime spot fishing rights at staggering prices (Møller, 2015), other areas can charge thousands of NOK (hundreds or thousands of euros) for their fishing rights, and others again only require a simple fishing card (inatur www.inatur.no).

This may be among the reasons why Kjelden et al. (2012) states most studies on value creation only study demand effects due to indirect effects being hard to quantify. We will therefore continue to use a qualitative method for exploring value creation for the local economy, beginning by quoting from Andersen, Stensland, Aas, Olaussen, and Fiske (2019):

> *Direct effects* are activities that are caused by increased income for:
>
> (1) The landowner who rents out the fisheries, and perhaps offers food and lodging in addition. (2) Other local businesses (such as grocers, sporting goods stores, and the hospitality industry) through supplying goods and services to the fishers and (3) the municipality through higher taxes as a result of greater economic activity.
>
> What we here call *wider economic impacts* consists of (1) *indirect effects* which are activities that are created as a result of increased income for local sub-contractors for goods and services, as well as any municipal activity, and (2) *induced effects* which are increased economic activities as a result of increased income for employees and owners in the local economy, as well as in the municipality (increased tax income as a result of increased activity in the municipality).
>
> (Andersen et al., 2019)(trans: ours)

In addition to Andersen et al. (2019) a very similar definition is used in Andersen and Dervo (2019), and the same economic multiplier as in both are used in Kjelden et al. (2012). Since all three are published by NINA (Norsk Institutt for Naturforskning) it seems plausible they are all using the same economic multiplier.

An economic multiplier is a figure for how much total economic activity is generated for each unit of direct effect. Since both indirect and induced effects are mentioned this is a type II multiplier, so we will use the symbol M_{II} for it in this thesis:

$$(18) M_{II} = \frac{Direct\ Effects + Indirect\ Effects + Induced\ Effects}{Direct\ Effects}$$

Now in these studies they use the economic multiplier not just for revenue, but for value creation as well, we will therefore follow their example. Which means value creation for the local economy (V_{LE}) given direct effects (R_D) is:

$$(19) V_{LE} = M_{II} R_D$$

During our literature search we did not find any suitable existing models for the economic impact a single factor (like salmon lice) may have on the local economy, all other things being equal. We therefore developed what we believe is a new conceptual model (we will use a very similar model for section 6.5). Let us begin by taking the direct income from recreational salmon angling as R_{salmon}, which we stipulate can be defined as:

$$(20) R_{salmon} = R_{MaxSalmon} \cdot Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})$$

Where $R_{MaxSalmon}$ is the maximum direct income that could be gained from recreational salmon angling in a region.

$Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})$ meanwhile is a function that determines the quality of the fishery based on a variety of factors $X_1, X_2, \dots, X_n$ (representing diverse inputs) and $Y_{salmonlice}$ is a variable based on the influence from salmon lice in the area. Further we hold that:

$$(21) 0 \leq Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice}) \leq 1.$$

We believe that postulating the existence of $\mathrm{Q_{salmon}}$ function, at least for describing the decline of fishing quality, is reasonable given facts such as: the presence of *Gyrodactylus salaris* (a salmon parasite) is known to reduce income from recreational salmon angling (Andersen et al., 2019); mixing escaped wild salmon with wild salmon is known to reduce willingness to pay for fishing rights (Liu, Olaf Olaussen, & Skonhoft, 2011); and that privately subsidising ocean salmon fishers along the fjords not to fish, thereby increasing stocks, have improved angling tourism income (Kjelden et al., 2012); finally we have several studies where fishers have answered questionnaires about their fishing habits, and though it is not a strong effect the quality of fishing had some importance (Stensland, Aas, & Mehmetoglu, 2017) and bad fishing could discourage participation (Stensland, Fossgard, Andersen, & Aas, 2015).

In short, things that decrease the quality or quantity of fishing in a river will tend to decrease the potential fishing related income in that river, and vice-versa things that improve quality or quantity will increase income. We have not found any articles that contradict this.

That said we should discuss some likely objections to this simple model. The first and foremost is that after *Gyrodactylus salaris* infected the Lærdal river, it was eventually cured, but as we can see in Andersen et al. (2019) it never regained the same level of value creation. We also note that there are far fewer foreign anglers now than there were before (Andersen et al., 2019). Given that British anglers tend to be the most enthusiastic about the quality of the catch (Stensland et al., 2015), it is possible the maximum income $R_{MaxSalmon}$ has declined, but it is also possible there is a time lag in the Q_{salmon} function. This is something which should be studied further, but we do not think it invalidates our model.

As we have demonstrated, among things in section 6.1, increased amounts of salmon lice have a detrimental effect on the number and quality of wild salmon that will re-enter a river. It is in other words a factor that decreases the quality and quantity of fishing in a river, therefore it is necessarily true that:

$$(22)\,\frac{\delta Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})}{\delta Y_{salmonlice}} < 0$$

Or, for a very perverse function Q_{salmon}, we can at least be certain that:

$$(23)\,\left.\frac{\delta Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})}{\delta Y_{salmonlice}}\right|_{X_1=z_1, X_2=z_2, \dots, X_n=z_n, Y_{salmonlice}=z_{n+1}} < 0$$

But for simplicity we will assume the “nicer” version in equation (22) applies.

Let us now take the value creation for the local economy, V_{LE} and say that it is:

$$(24) V_{LE} = M_{II} \cdot R_{salmon}$$

We apply equation (20) and get

$$(25) V_{LE} = M_{II} \cdot R_{MaxSalmon} \cdot Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})$$

Thus, necessarily

$$(26)\ \frac{\delta V_{LE}}{\delta Y_{salmonlice}} < 0$$

If our assumptions are correct an increase in salmon lice will necessarily have a negative effect on the local economy.

6.5. Potential influence on landowners' income and property prices

There has recently been some discussion of whether salmon aquaculture has lead to lower property prices along salmon rivers (Klouman, 2017), however there does not appear to have been any systematic attempts to look into this. In this section we will make an attempt to correct this.

Initially it seems plausible when you consider, as Stensland (2010) brings up, that according to the Norwegian Salmonids and Fresh-water Fish Act of 1992 in which §16 a landowner by a river has exclusive rights to fishing for anadromous salmonids, while §19 stipulates that the fishing rights cannot be permanently alienated from the property. To quote "Farms or properties that historically acquired most of the good farmland next to the rivers are therefore the main holders of salmon fishing rights. The fishing right is a property right and thus defines who has access to the resource and under what conditions." (Stensland, 2010)

In section 6.4 we demonstrated that direct income from recreational salmon angling depends on the quality of the fishing ground, and that part of the quality of the fishing ground is the quantity and quality of the fish-stock which can be influenced by salmon lice. So, the fishing right creates a potential income for the landowner. Even a cursory investigation (partly through (Norske Lakseelver) at www.lakseelver.no) revealed that how fishing rights are administrated varies enormously we will concentrate on those areas where the landowner leases out their fishing-rights or receives other income from recreational salmon angling (whether directly or through a third party).

For our purposes this income can be seen as a form of farm income, subject to many of the same restrictions: It depends on the price (in a wide sense) of a natural resource harvested on your land. There exists a variety of studies old and new as to the valuation of farmland

(Devadoss & Manchu, 2007; Reinsel & Reinsel, 1979; Weersink, Clark, Turvey, & Sarker, 1999), and so we can turn to these to see how salmon lice might affect the price of properties with accompanying fishing rights.

The question of farmland prices is a complex one, with many possible methods of solving it such as: supply and demand; net present value; demographic factors; and empirical models (Devadoss & Manchu, 2007). This is further complicated by issues such as government subsidies (Devadoss & Manchu, 2007; Weersink et al., 1999) and varying crop-prices (Devadoss & Manchu, 2007). In addition, we have that expectations of increase land prices in the future can affect land prices today (Weersink et al., 1999).

We should point out that this is in line with the circular from Landbruks- og matdepartementet (2002) (Eng: Ministry of Agriculture and Food) stating that agricultural and forestry revenues, rental value from houses, and the potential revenue from other rights or resources are to be used for assessing the value of a property.

The normal net present value for property prices would look like this:

$$(27) L_t = \sum_{i=1}^{\infty} \frac{E(R_{t+i})}{(1+r)^i}$$

However, as Weersink et al. (1999) points out, it is entirely possible to split up the income from the property into its constituent sources (their example was production and government sources).

We cannot see why this principle could not be taken further, so building on the standard NPV model we develop our own model. As far as we are aware no one has tried to show how salmon lice (And potentially other blights on salmon fisheries) can affect property prices along salmon rivers.

In equation (28) we see how the NPV of property prices (L_t) at any time *t* can be divided up into various revenue streams $R_{j,t+i}$ with their own appropriate discount rates r_j.

$$(28) L_t = \sum_{i=1}^{\infty} \sum_{j=1}^{n} \frac{E_t\left(R_{j,t+i}\right)}{\left(1+r_j\right)^i}$$

We can now simplify this to:

$$(29) L_t = L_{other,t} + \sum_{i=1}^{\infty} \frac{E_t\left(R_{salmon,t+i}\right)}{\left(1 + r_{salmon}\right)^i}$$

Here $L_{other,t}$ is the part of the land value contributed by all other factors, while $R_{salmon,t+i}$ is the total income from recreational salmon angling at the time $t{+}i$. Let us now stipulate that we may define $R_{salmon,t+i}$ thus:

$$(30) R_{salmon,t+i} = R_{MaxSalmon,t+i} \cdot Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})$$

Which as we can see is almost the same as equation (20), except that $R_{MaxSalmon,t+i}$is the highest amount that the landowner could gained from recreational salmon angling, that is to say the value of the best possible product for this area at the time t+i (thus it automatically takes into account growths in international angling tourism).

$Q_{salmon}(X_1, X_2, \dots, X_n, Y_{salmonlice})$ meanwhile is the same as in equation (22).

And by extension (if we combine equation (29) and (30)) we get:

$$(31) \frac{\delta L_t}{\delta Y_{salmonlice}} < 0$$

And so, given our assumptions, we see that increasing the amount of salmon lice will decrease the property price.

6.6. Municipal benefits from aquaculture

This is somewhat outside of the scope of this thesis, but present or anticipated future economic benefits is part of why municipalities might support aquaculture. This helps inform sections 6.7 (Externalities), 8.4 (Norwegian rural development policies), and 8.5 (Tax on economic rent).

Why ask about municipal benefits instead of national benefits? Because costs and benefits may be unevenly distributed. In Norway there is a strong tradition of local government (this even extends to aquaculture (Kvalvik & Robertsen, 2017)), so municipalities who gain or lose disproportionally will have a motive for taking action.

So, the first thing we need to ask ourselves is this: What municipalities benefit from aquaculture? At first it may seem obvious that only those municipalities with direct aquaculture activities, be it fish-farms, fish slaughterhouses, or other processing facilities, will profit from aquaculture. Yet this ignores the widespread wider economic impacts from the primary activities, a study by Robertsen, Iversen, and Andreassen (2015) in Rogaland and Hordaland showed that there was considerable multiplier effect. For instance, companies in Oslo may supply natural gas to the industry, while a company in Sogn-og-Fjordane supplies plastic, both of them outside the region with the primary aquaculture activity (Robertsen et al., 2015). This is not simply an aberration for Rogaland and Hordaland, for as both Andreassen and Robertsen (2014) and the aquaculture industry has a wider economic impact nationwide.

In 2017 the salmon aquaculture industry alone had a primary income of 61 200 million NOK (approximately 7 000 million USD) on a national level (Statistisk sentralbyrå, 2017). Yet in Robertsen et al. (2015) we see that the jobs and benefits are very unevenly distributed. This is further supported by Hersoug et al. (2014) who comment on how there is immense variation in how the wider economic impacts are dispersed. There is also great variation how important the industry is for a municipality, with numbers ranging from 20% of every employed person, to under 2% (Hersoug et al., 2014).

However there appears to be a general feeling that the municipalities are not properly compensated for allocating areas to aquaculture (Kvalvik & Robertsen, 2017). This concern came at least in part after new regulations and resulting structural changes in the aquaculture industry has concentrated the value creation in fewer, larger areas and facilities (Hersoug et al., 2014).

It was as a result of this uneven distribution of benefits and to reward the municipalities for the work they had done in allocating new areas the Norwegian government created Havbruksfondet (Regjeringen, 2016). Havbruksfondet will divide all future income from expansion (production capacity adjustments) of the aquaculture industry (that is to say from new licenses and increased maximum allowed biomass) between the state (20%), the counties [Fylkene] (10%), and the municipalities (70%) (Fiskeridirektoratet, 2017). However, this income only comes from expansion, and when expansion is allowed and in what form has varied enormously over the years (Mikkelsen et al., 2018).

As a result of these concerns a commission has been appointed to study whether economic rent taxation should be imposed on the aquaculture industry (Finansdepartementet, 2018). This would have the benefit of guaranteeing the local municipalities a large slice of the pie, as well as a more stable revenue stream (Mikkelsen et al., 2018). The results of the deliberations are not out as of the writing of this thesis, but given the trend of increasing regulation and taxation we believe it is likely to be recommended.

In the future global warming is not just likely to make farmed salmon grow somewhat faster, but will also encourage aquaculture facilities to move further north (Lorentzen & Hannesson, 2006). This will obviously benefit northern municipalities would stand to gain a safe and lucrative revenue stream, provided they receive the benefit of any economic rent taxation,. We cannot say anything beyond that at this time, since we have not yet seen the result of the commission's deliberations. For example, we cannot rule out that the economic rent tax, if it happens, would go entirely to the state.

6.7. Externalities

After going over several aspects of the effect of climate change on salmon lice, it is natural to ask: Are any of these externalities?

Since there are a great many competing definitions of externalities, we will explicitly define what we, in this thesis, mean by an externality. We will then attempt to show how this definition applies to the issues we have discussed earlier in this chapter. After which we will discuss the way they influence public discourse, and cause government attempts to regulate them.

6.7.1. Definition of an externality

How to define externalities is vital to this thesis, we want a definition that is rigorous, and which can account for both monetary loss and intangible values. We therefore refer to the article "Externality" by Buchanan and Stubblebine (1962) published in Economica, which states that when the utility of an individual A depends on some activity of another individual B, then an externality exists. Or in mathematical terms the utility function of A is:

$$(32)\ u^A = u^A(X_1, X_2, \ldots, X_m, Y_1)$$

(Buchanan & Stubblebine, 1962).

With the partial derivative of the function represented as:

$$(33)\ \frac{\delta u^A}{\delta Y_1} = u^A_{Y_1}$$

Where Y_1 is some activity under the control of B, in our case the decision is to continue operating salmon aquaculture, which results in an increased number of salmon lice. (Buchanan & Stubblebine, 1962). Thus, giving us:

$$(34) u^A_{Y_1} < 0$$

That is the derivative of the utility function with respect to Y_1 is negative, giving us a marginal external diseconomy. Which is to say A is negatively affected. (Buchanan & Stubblebine, 1962).

However, we must acknowledge that salmon aquaculture could have a benign effects on external actors, such as providing municipalities and marginal coastal communities with much needed additional income. Let us call this activity Y_2. The problem of course is in judging whether these are marginal economies, e.g. increasing the activity would increase utility:

$$(35) u^A_{Y_2} > 0$$

(Buchanan & Stubblebine, 1962).

Or if they are an infra-marginal external economy, so incremental increases in the activity would not increase utility, but the activity occurring at all does increase utility.

$$(36) u^A_{Y_2} = 0, and \int_0^{Y_2} u^A_{Y_2} dY_2 > 0$$

(Buchanan & Stubblebine, 1962).

So, a municipality or community might suffer the effects of lost income from angler tourism (Kjelden et al., 2012; Stensland, 2010; Tiller et al., 2012), but at the same time receive some income from local interests who own facilities or from jobs being provided (Mikkelsen et al., 2018; Ridler, 1997), and possibly being able to extract fees or taxes (Finansdepartementet, 2018; Tiller et al., 2012). This in addition to the intangible local values that could be lost due to the increased population of salmon lice.

There can be great difficulty in finding good quantitative data, especially since the circumstances of different municipalities can vary enormously. However, if we assume rational actors who want to increase their utility, then there is a test to see how they think their utility is affected:

> An externality is defined as potentially relevant when the activity, to the extent that it is actually performed, generates any desire on the part of the externally benefited (damaged) party (A) to modify the behaviour of the party empowered to take action (B) through trade, persuasion, compromise, agreement, convention, collective action, etc. An externality which, to the extent that it is performed, exerts no such influence is defined as irrelevant. (Buchanan & Stubblebine, 1962)

So in the case of municipalities one measure of how they view the aquaculture industry will be the actions they take to make said industry modify their behaviour, say by making it easier or harder to establish new localities in their zone of control (Hersoug et al., 2014; Tiller et al., 2012).

For other agents we, where it is easier to find good sources and to define conflicts of interest, we will be looking at economic losses as well as examining their actions in regards to salmon aquaculture (co-operation, resistance, non-action etc).

6.7.2. Does the salmon aquaculture industry cause externalities?

Yes.

At least as far as salmon lice are concerned.

There are, of course, other potential externalities such as escapes, organic waste, pharmaceuticals or chemicals entering the local wildlife, disease, and so on. But this class of externalities are beyond the scope of this thesis, and we will concentrate on salmon lice.

Section 6.2 shows that separate aquaculture localities can cause each other infections, which as section 6.3 shows leads to economic loss.

Section 6.1 shows that sea-lice caused by aquaculture harms the stock of wild salmon. Afterwards section 6.4 shows that this leads to economic losses (or reduced value recreation) for local communities. While 6.5 shows it leads to economic losses for landowners, as well as potentially lower real estate prices.

Since we assume that having more rather than less money is good, then if we say party B is a nearby aquaculture operator (close enough to affect party A), we have that:

$(37) u^{A}_{Y_{aquaculture}} < 0$

Since the aquaculture operation of party B will lead to economic loss, therefore diminished utility for A. Which is in line with the first test we described in section 6.7.1.

Except we also have section 6.6 which shows that several municipalities already benefit from aquaculture, but that the degree to which they benefit is likely to greatly increase in the near future. Which means that for these municipalities we have that:

$$(38) u^{A}_{Y_{aquaculture}} > 0$$

Or the more local aquaculture (that they get paid for) there is the better their situation is.

However, the second test is that party A take some action to modify the behaviour of party B. We propose that in a country such as Norway such action ideally comes in the form of engaging in public discourse and lobbying for new and improved regulations, or other political measures. At least we have not found any evidence of other methods being in use.

This second sense is also important because if A does not take action to modify Bs behaviour, then as Buchanan and Stubblebine (1962) states the externality B causes A is irrelevant.

6.7.3. Public discourse about aquaculture

We should first state that it is not entirely uncontroversial to claim that aquaculture causes negative externalities. For instance, Reppe (2015) argues that the hydropower industry is escaping without blame, and in an interview again by Sætre and Østli (2017) questions the validity of modern research on the topic. The same is true for Gjøvik (2011-2019) who on the website Aquablogg seeks to challenge the commonly held views of the research community. Most relevant to this thesis is the hypothesis that salmon lice from aquaculture is not a significant threat to wild salmon (Gjøvik, 2011-2019). Indeed, these views were presented in a rapport of his which was specifically rejected by the Institute for Marine Research (Hosteland, 2015).

Likewise we have from Myklebust (2019) that, among other things, the Facebook comment sections are often the place for very frank exchanges of views on the subject of aquaculture and its environmental and economic impact. Though occasionally to the point of exceeding the bounds of decorum and carefully reasoned debate that we have come to expect from the comment section of Facebook and other internet forums (Myklebust, 2019).

To a great degree the relationship between aquaculture and other coastal stakeholders is one of conflict. It is no wonder that Osmundsen and Olsen (2017) called their article “The imperishable controversy over aquaculture”, and what they describe are two sides both lacking in nuance who fight it out in the media, constantly rehashing the same arguments. This is somewhat concerning since, as Olsen and Osmundsen (2017) points out, the media tells us what to think about and what to think about it. If at the same time a person who gets involved will simply pick a side and stay with it, or at least the two sides do not change, (Osmundsen & Olsen, 2017) then resolving the issues through debate alone gets trickier.

As an example of the polarization we have how Havforskningsinstituttet (Institute of Marine Research) is both accused by the environmentalists of being a pawn of the aquaculture industry (Andenæs, 2012) and by certain members of the aquaculture lobby of being against the same industry (Myklebust, 2019; Myklebust & Rogne, 2016). It is perhaps an indication of a certain level of polarisation that anyone who is not fully with you, must be a pawn of the enemy.

That the controversy has not changed much is perhaps most clear from the fact that Andenæs (2012) and Osmundsen and Olsen (2017) pretty much report on the same reality. Overall both Osmundsen and Olsen (2017) and Andenæs (2012) go into what level of positive and negative media coverage the aquaculture industry gets, and both agree that there is more negative than positive media attention. However, it is also clear that the industry is trying to promote its own views (Osmundsen & Olsen, 2017) and that the industry is also portrayed as offering great financial opportunities (Schlag, 2011).

When it comes to salmon lice in particular, it is clear that it is a major reason for opposition from environmentalists (Andenæs, 2012), sports fishers and those associated with angling tourism (Osmundsen & Olsen, 2017). Far from being a neglected aspect media attention on the environmental dangers of aquaculture have a strong focus on salmon lice and salmon lice treatments (Olsen & Osmundsen, 2017). If we look at future developments, namely that we in chapter 5 (section 5.10 in particular) have shown that the problem with salmon lice can soon get worse, we need to bear in mind that the Norwegian public is already concerned about global warming (Austgulen, 2012; Pidgeon et al., 2017). This could perhaps feed into the already existing environmentalist worries about aquaculture (Andenæs, 2012), especially those regarding how sea lice are already attacking the wild salmon (Olsen & Osmundsen, 2017).

What we see is that the various stakeholders in both the industry subject to externalities are actively pushing their own agenda in the media. It is generally known that it takes some non-trivial effort to push your views in the media, and the fact that this effort is made shows that the externalities in question are non-trivial. Further, since one of the physical causes of greatest concern (salmon lice) is influenced by another factor of great concern (global warming) it is possible that the issue will become even more inflamed. Certainly, there is no indication that it will go away.

6.7.4. Regulatory and political responses to the externalities

Let us point out that public debate influences politics, and politics influences public debate (Olsen & Osmundsen, 2017), and likewise the political culture helps to frame debate (Schlag, 2011). Therefore, we cannot fully separate regulations, politics and the media. Smaller organisations such as Elvene Rundt Trondheimsfjorden may find it difficult to play the political game, but they do try to do so (Kjelden et al., 2012). Nor are scientific organisations allowed to stay out of the political game, if their findings are used to justify regulations (Myklebust, 2019).

We may not be able to judge the degree to which pressure from various interest groups shaped these policies and regulations, but we do feel we have shown that they have an influence.

Returning to salmon lice Norway already has many measures restricting the ratio of adult female fish to salmon (Liu & Bjelland, 2014; Nærings- og fiskeridepartementet, 2012; Revie et al., 2009), but recently a new measure popularly called the traffic light system has been introduced (Karlsen et al., 2016)(See Table 3) Though as we have mentioned earlier you can still apply for a permit to expand in the red zones (Fiskeridirektoratet, 2018) and for now there will be no production reduction in the red zones (Nærings- og fiskeridepartementet, 2017). However, according to Nærings- og fiskeridepartementet (2019) there is a hearing underway about a proposal to make cuts in the permitted salmon biomass in red zones, but the results are not out yet.

These developments point to a trend shown in Mikkelsen et al. (2018) and Hersoug et al. (2014) of increasingly strict regulations and conflicts over both environmental and economic issues. Even if the implementation is slow in this case we feel confident it will come in and get increasingly stricter. This is significant when we come to section 6.7.3 about public debate, where we among other things discuss the protests of environmentalist organisations (Woie, 2018).

In section 5.9 we briefly mentioned firewalls, and it is now time to return to that topic. Given the great historical importance of wild salmon (see chapter 3) and the increasing environmentalist hostility to aquaculture (see section 6.7.3) it is not surprising that measures have been taken to protect national salmon fjords and areas near important rivers (Serra-Llinares et al., 2014). These measures had less efficient predecessors, where some administrative areas would protect a salmon fjord, while others wouldn't (Tiller et al., 2012), but eventually a stronger nationwide regulator effort was introduced (Serra-Llinares et al., 2014).

Not only does the existence if these firewalls support our findings in section 5.8, but real-world data indicate that they do grant some degree of protection (Serra-Llinares et al., 2014). Firewalls have also been found to be quite useful to deal with other issues, such as halting the spread of pancreas disease (Tavornpanich et al., 2012).

The system of firewalls could possibly be expanded given that there is pressure from both environmentalists and other stakeholders interested in wild salmon, as well as a proven record of effectiveness. If so this would seem to be in line with the issues raised by Tiller et al. (2012) and Kvalvik and Robertsen (2017), namely that increased intermunicipal or regional co-operation and regulation could be necessary in the future.

That said, it should be born in mind that aquaculture is a 61 600 million NOK industry (Statistisk sentralbyrå, 2017) while the total revenues for salmon angling in Norway were 1 260 million NOK (plus another 1 060 million NOK for indirect effects) the next year (Andersen & Dervo, 2019). Another number is that in 2011 tourist sea fishing brought in 851 million NOK (Borch, Olsen, & Moilanen, 2011). In short fishing tourism in total is a drop in the ocean compared to salmon aquaculture alone, but despite this the regulations keep tightening, and we see no reason to think this will stop.

All the same we repeatedly see various stakeholders lobby for political and regulatory action to negate the externalities that they are exposed to. Given that as the problem increases (see sections 5.1-3 and 6.1-2,5-6) further regulations may be necessary, it seems unlikely that these actions are going to diminish.

7. Relevant factors outside the scope of this thesis.

In researching our thesis, examining the gathered data, and carrying out our simulations we came across factors that were at the same time relevant and yet somewhat outside the scope of the thesis. Though we have limited the scope of our thesis, we have decided to briefly go over a few factors that are either easily addressed or else too important to ignore.

7.1. Decreased salinity from increased rainfall and melting of the polar ice

The samples from the ROMS dataset also contained salinity data for our Virtual Area Locations (VAL). This was interesting because from the work by Bricknell, Dalesman, O'Shea, Pert, and Jennifer Mordue Luntz (2006) we know that salinity affects salmon lice settlement success. That is their chance of infecting their victims, since our model is based around infection pressure this is obviously relevant. We also have models of the salmon lice life cycle that takes this into account (Rittenhouse et al., 2016), and it is well known that salmon lice avoid low salinity areas (Kristoffersen et al., 2018). Again showing the potential relevance.

A cursory study of the salinity data showed a downwards trend, which is to be expected according to Curry and Mauritzen (2005) who comments on “[Glacial] melting, enhanced precipitation, and continental runoff, which are projected to increase freshwater input to the Arctic and sub-Arctic seas”. In a similar vein Durack, Wijffels, and Matear (2012) use the metaphor “the rich get richer” to address the changing salinity of the north Atlantic water, by which they mean “salty ocean regions (compared to the global mean) are getting saltier, whereas fresh-regions are getting fresher”.

However, the lowest level of salinity found in our sample, looking at the period 2013-2069, was a salinity of 31.34 grams per litre for the Bergen VAL in February 2060. This is well above the minimum threshold for a negative effect found in Bricknell et al. (2006). In other words, we believe salinity would be of so marginal impact that we picked a model that did not use it.

On a further note we are aware of how Shephard et al. (2016) show that rain can negatively affects salmon lice, and that Revie et al. (2009) comment on how sea lice have difficulty dealing with brackish water. So increased rain and waterflow in rivers might make some areas less saline than today, particularly near river deltas, but both given the lack of truly major rivers in Norway and the scope of this thesis we will not touch on it here. It is however potentially good material for future studies.

7.2. Salmon lice resistance to treatment

Salmon lice resistance to treatment is a serious concern in several studies (Costello, 2006; Iversen et al., 2017; Jansen et al., 2012), and the model of Aldrin et al. (2017) even take potential differences in resistance level and make it a variable. Indeed the salmon lice has already developed resistance to several treatments and there is a concern that if this process continues there is no new set of medication to step in (Revie et al., 2009). Although, so far, we have found that H_20_2 baths still work in spite of growing resistance to other treatments (Iversen et al., 2015), but these chemical baths have their own drawbacks such as stunting growth (Liu & Bjelland, 2014), and requiring larger amounts of manpower (Iversen et al., 2015).

Further, looking at Mattilsynet og Fiskeridirektoratet (2010) study on fish cage sizes, we note that in recent years there has been a growth in said size. Should the continued expansion of the aquaculture industry lead to this development continuing, there are indication that this would be particularly conductive to salmon lice developing resistance. In addition large fish-cages would make chemical bath treatments harder to carry out properly (Mattilsynet og Fiskeridirektoratet, 2010).

However, since this would require us to do studies on drug resistance, which would add another variable, we decided to leave it be. Especially since Rosten et al. (2011) outright states that there is no coordinated collection of data on treatment resistance among salmon lice. Instead we picked a study that ensured “antiparasitic treatment did not affect lice abundances in the data” (Kristoffersen et al., 2014). The topic, though important and very interesting, is fully beyond our scope.

7.3. Salmon resistance to salmon lice (Including a vaccine)

Revie et al. (2009) states that “In the longer term, continued mortality of wild fish will likely select for resistance to lice[.]” Then continues to describe that increased resistance has been documented in the wild and that there might be local variation thereof. Therefore it may be possible to selectively breed for such resistance (Revie et al., 2009). A very similar argument is also put forward by Torrissen et al. (2013). This would of course be very good if it happens, but our first source discussing differences in susceptibility between salmon breeds is Johnson and Albright (1992), and this very year we have the article “Catching the complexity of salmon-louse interactions” Gallardo-Escárate et al. (2019). It would be very good if we could breed a salmon lice resistant salmon, but we are uncertain of the time scale.

Now as for a vaccine. Well. The first mention of a salmon lice vaccine we could find was Pike (1989), and we see that afterwards Rae et al. (2002) mentions it, so does Revie et al. (2009), and then there is Torrissen et al. (2013) who states “Thus, the development of a vaccine against *L. salmonis* in Atlantic salmon remains a long-term goal”. We agree that a vaccine against salmon lice would be a very good thing if we could get one, but so far it seems speculative.

In both cases, salmon lice resistant salmon or a vaccine, it is clear that it would be a good thing if it could happen what is uncertain is when, how, or even if such a thing could come about. As a result, we decided not to speculate about it, and exclude it from the scope.

But if we should speculate, full success in either area would simply put remove aquaculture as a negative externality vis-à-vis salmon lice. Since it would remove the fish-cages and aquaculture localities as breeding grounds for the salmon lice.

7.4. Future technologies

We believe that chapter 6 adequately shows that the salmon lice problem is so large that one ought to pursue solutions for it. Further, we have from Pidgeon et al. (2017) that the general public is favourable towards technological solutions for climate change related problems. It therefore seems natural to turn towards technological solutions for the salmon lice problem, since it could potentially help with the infection problem as well as lead to more favourable public reactions.

Future technologies run the gamut from run the gamut from underwater drones shooting lice with drone mounted lasers (Dumiak, 2017; Stensvold, 2017), to closed fish-farms (Rosten et al., 2011), and to wrapping plankton nets (Grøntvedt, Kristoffersen, & Jansen, 2018) around the fish-farms. There is a great number of issues to look into for all of these, their feasibility, effectiveness, and cost-benefit analyses for one. This is not even going into issues like comparative carbon footprints between land-based and ocean based technologies, or how this depends on where you get your electrical supply (Liu et al., 2016).

Closed aquaculture facilities (at sea or on land) were the only ones we could find good financial data for, so we will focus on them. Although items like the article “Lice-hunting underwater drone protects salmon” Dumiak (2017) are certainly fascinating from a technical point of view, there are no comparative economic studies on this technology. Cleaner fish is another potential technology and we found it mentioned in Liu and Bjelland (2014), Nilsen et al. (2017), and Costello (2006), among others. Likewise, we see that raising blue mussels in the same facility as salmon, may help reduce the number of copepodites (Molloy, Pietrak, Bouchard, & Bricknell, 2011). This is very much in line with the sort of integrated aquaculture system recommended by environmental organisations like Bellona (Karlsson-Drangsholt, Nes, & Bellona, 2017). Yet it has proven very difficult to find precise figures on their costs, benefits and so on of these more unusual solutions.

One key problem with estimates for closed aquaculture facilities is that even today we are mostly relying on simulations and estimates for our knowledge of the construction and operational costs (Iversen, 2019). Feasibility studies by Rosten et al. (2011) appear to find the technology promising, but are not convinced it is economically feasible. Yet Iversen (2013) and Liu et al. (2016) both give estimates of operational costs and initial investments that, though higher than open pens, are not stated to be prohibitively so.

Revie et al. (2009) states that the only way to completely protect farmed salmon from salmon lice is to keep them entirely closed off from surrounding waters. This would effectively mean on-land facilities with full recycling (RAS), which Liu et al. (2016) suggest would not necessarily be prohibitively expensive. This would be in line with Iversen (2013), who also rates on land fish-farms as the best for preventing salmon lice infection.

When it comes to at sea facilities (be they off-shore, or closed fish-farms closer to shore) Rosten et al. (2011) expresses some caution when it comes to their ability to filter water. However, the concerns of Rosten et al. (2011) seem to be mainly aimed at viruses and other diseases that are harder to stop than salmon lice. Further, we have Nilsen et al. (2017) who describe how even a simple mechanism pumping up water from further down the water column was effective at reducing salmon lice infection. Likewise Iversen (2013) describes the various closed fish-farms at sea as having better protection from sea-lice than their current open-net counter-parts.

Both Rosten et al. (2011) and Iversen (2019) (the latter in his interview with us) mentions that there is still the need for further research, and that it is not clear how competitive these technologies will be.

The one consistent factor across time and technologies is that all methods taken to stop salmon lice increase production cost and may also increase initial capital investment.

We have chosen not to fully compare the effectiveness of various technologies or to give advice as to which should be selected, whether in the short, medium, or long run. This would be outside the scope of this thesis. However, we do think this is such an important matter that it required at least a brief overview.

7.5. The intangible value of wild salmon

What is the value of having wild salmon at all? As we can see in chapter 3 there is a long and illustrious history of Norwegians engaging with the salmon and arguing over it. Environmentalists have roundly condemned the aquaculture industry (Andenæs, 2012) and the language of purity used when arguing against it in general suggests an appeal to intangibles (Olsen & Osmundsen, 2017).

Given that our definition of externalities is quite capable of tackling the topic of intangible values, since it deals with utility and not money, it may seem strange to neglect it. However, any discussions of this cultural value would have to deal with the Sami people and their heritage. As Borch, Buanes, Karlsen, and Olsen (2009) rightly points out this is not simply an economic issue. Yet, as we asked earlier, is it really a purely economic issue for all Norwegian areas? Given a history of salmon fishing going back to the Viking ages (Berg, 1986), it is hard to think it could simply be a matter of money.

Navigating this difficult and sensitive topic would require a separate thesis, preferably one of an interdisciplinary nature. We have therefore not gone into this topic in great depth.

8. Suggestions for future action

In this chapter we will go over some possible ways of dealing with the salmon lice problem. Our goal is not to create a final list, but to discuss some options that stood out to us during our research.

8.1. Active awareness of global climate change

We have not found any articles or other works on the topic of how global climate change will affect the fecundity and life cycle of salmon lice, and from there influence both salmon aquaculture and wild salmon. We believe that we have exercised due diligence in searching for this. When we contacted informed academics and interest groups, none of them suggested any works on this topic.

Given our findings documented in chapter 5 and 6 we believe that we have shown there is great potential for global warming to exacerbate the salmon lice issue. Further, looking at sections 5.10 and 6.1 we would like to point out that the surprising spikes we noted could have various detrimental effects, and the first one might arrive in the near future. We do not know how bad the effect would be, or if there are other potentially nasty surprises that could be uncovered in advance if more attention was paid.

We believe that both the industry and the Norwegian government should pay more attention to how global climate change can affect this and other issues. In particular we would like to see better and more detailed projections of future ocean temperatures, the ROMS temperature data is good, but we only have a single forecast.

It seems likely that even modest investments could be very helpful for spotting new threats in advance.

8.2. Technological solutions

As we have mentioned previously technological solutions are viewed positively when it comes to climate change (Pidgeon et al., 2017), so there is no reason to think that the public would not be similarly positive to technological solutions to the salmon lice problem. This could be important given the political game that is on regarding access to locations on the Norwegian coast (Hersoug et al., 2014; Isaksen et al., 2012; Osmundsen & Olsen, 2017).

The industry hardly needs persuading that research is necessary, for there is already considerable active research going on, even if it has yet to overcome all the technical and economic issues (Iversen, 2013; Liu et al., 2016; Rosten et al., 2011). From what we have seen the industry is actively pursuing solutions and will presumably implement them when they become economically viable or future regulations compel them to do so.

To support this, we can look at among others Rosten et al. (2011), here we see an analysis of a wide array of closed fish-cages: flexible bags; solid walls (concrete or metal); in pipes; in boat hulls; and even in giant aquadomes. Likewise, we have a set of proposals for land based systems, with various types of water purification technology (Rosten et al., 2011). Pilot land based projects have already been built and there have even been studies on their carbon footprints, with one issue being whether they use clean hydropower or coal based power (Liu et al., 2016). We have tests showing that even simple plankton nets would reduce the threat of salmon lice (Grøntvedt et al., 2018), as well as a study on closed flexible bag fish-cages showing near zero infections (Nilsen et al., 2017).

On the subject of vaccines and breeding resistant salmon we have talked about some of the issues in chapter 7. If it could be done it would be good, indeed it might be very cost-effective, but as we said before unlike other technological solutions it is hard to predict how and when it would come about.

The real problem these technologies try to solve is how salmon lice copepodites infect farmed salmon, grow to sexual maturity, and proceed to procreate spreading more larvae. These then become infectious copepodites and spread across the sea to infect farmed and wild salmon, continuing the cycle (Kristoffersen et al., 2014; Revie et al., 2009). A technological solution that could prevent one of these steps, either prevent initial infection, or prevent the spread within the fish cage, or prevent the spread out of the fish-cage, would effectively reduce the problem to a nuisance.

The issue is of course that as Shainee, Ellingsen, Leira, and Fredheim (2013) states we need to reduce the solution to an economically feasible cost. Though from Iversen (2013) we do see that even in 2013 there were promising solutions, and in a private communication Iversen (2019) informs us that developments are ongoing (though price estimates remain higher than for open fish-cages). We are therefore quietly confident that there are technological solutions to at least alleviate the problem, though they will increase costs.

8.3. Firewalls

As we see in section 5.9 and discuss in section 6.7.4 firewalls are one of the methods used for dealing with salmon lice and other infestations. From Serra-Llinares et al. (2014) we also see that some degree of success is suggested, but the question is of course why there is only some degree of success given our results in section 5.8-9 which suggest that distance is the key factor. The answer to this is implied in section 6.1.2 where we discuss the migration routes of the salmons: Since they do not necessarily follow the straightest route out, it is possible that they will pass by an aquaculture locality lying at some distance from the protected area (Olaussen et al., 2015; Revie et al., 2009).

There is also the self-evident fact that excluding salmon aquaculture from an area means excluding salmon aquaculture from that area. Given that we already have a shortage of suitable localities (Hersoug et al., 2014) this is not a trivial consideration, especially when we consider that the excluded areas can be as large and centrally placed as Trondheimsfjorden (Serra-Llinares et al., 2014).

Yet they cannot be excluded as one of the measures taken to protect the wild salmon, especially in light of efforts to increase inter-municipal co-ordination (Kvalvik & Robertsen, 2017; Tiller et al., 2012). This is doubly true since the benefits are not necessarily limited to salmon lice, but might also cover other diseases (Tavornpanich et al., 2012). Though caution may be called for given the existing difficulties in finding good localities for salmon aquaculture (Hersoug et al., 2014), firewalls appear to be a legitimate tool to reduce the infection pressure from salmon lice.

8.4. Norwegian rural development policies ("Distriktspolitikk") and the flight north

Norwegian rural development policies have been a key aspect of Norwegian politics for a very long time (Mikkelsen et al., 2018) and continues to be an important part of government policy making (Kommunal- og moderniseringsdepartementet, 2019). Further the northernmost areas of Norway have been an area of particular interest Norwegian the rural development policies (Kommunal- og moderniseringsdepartementet, 2018; Mikkelsen et al., 2018). We can find no reason why this would be subject to change in the foreseeable future.

Both Lorentzen (2008) and Lorentzen and Hannesson (2006) go into some length as to how aquaculture conditions in the north of Norway will improve as a result of global warming. We have in Lorentzen and Hannesson (2006) several scenarios which shows different effects on how much the rules for aquaculture are reformed in the near future. As a rule the more liberalized they were the more of the operations would be shifted north (Lorentzen & Hannesson, 2006).

We have also in chapters 5 and 6 shown that the absolute increase in salmon lice is and will continue to be less troublesome in northern Norway than in the south. It therefore seems plausible that we might need to relocate the point of gravity of the aquaculture industry further north. Not only would this be pragmatic, but such a move would benefit rural development policies.

Both the industry and government (local and national) should bear this fact in mind when developing future plans, since it is not entirely clear how quickly the extreme effects of global warming might reach us.

8.5. Tax on economic rent

Recently there has been debate about adding a tax on economic rents for the aquaculture industry, which has led to a committee being set down to review the issue (Finansdepartementet, 2018). Of course, leaders of the industry have claimed that there is no such economic rent and that such a tax would only serve to drive aquaculture away from Norwegian shores (Lier-Hansen & Ystmark, 2019). Whether or not the aquaculture industry has economic rents or not is of course an interesting question, which could be debated at length, but it is beyond the scope of this thesis.

A pragmatic argument in favour of such a system of economic rent taxation might benefit the municipalities currently harbouring fish-farms, which would also make them more favourably inclined towards aquaculture. Previously groups like the NFKK (Nettverk for Fjord- og Kystkommuner, eng: Network for Fjord and Coastal Municipalities), a group founded to protect the interests of member municipalities (NFKK, 2019), have expressed frustration with the aquaculture industry and reluctance to make further allocations (Isaksen et al., 2012). Meanwhile we have the fact reported by Hersoug et al. (2014) that while local interests owned the aquaculture facilities, and the jobs and income were kept in the local communities, then the municipalities were fairly friendly towards the industry.

Since it is increasingly difficult for the aquaculture industry to get good localities (Hersoug et al., 2014), localities that are assigned by the municipalities (or coalitions of them) (Kvalvik & Robertsen, 2017; Tiller et al., 2012) it could be argued that it would be beneficial to make the municipalities more favourably disposed towards the industry.

However, there is another side to the argument, which is that such a tax would necessarily cut into the profit margins of the aquaculture industry, making future investments less desirable.

This is doubly important when we consider that all of the various closed fish-farm concepts are more expensive than open fish-cages, both in terms of initial investment and in cost per kg of salmon produced (Iversen, 2013). Moreover, there is still a need for further research on many of these technologies (Nilsen et al., 2017), which will also require investment.

As we argued in section 6.3 the increase in salmon lice infection pressure will lead to increased production costs for the industry, which, all other things being equal should encourage research into technological solutions. However, if a tax on resource rent is applied it might make such investments seem less desirable. Discouraging such investments could also mean that the problems discussed in 6.4 and 6.5 would continue to worsen.

A full discussion of this topic is beyond the scope of this thesis, which is why we remain agnostic as to whether or not a resource rent exists or not. These are not simply economic facts, but also have a political dimension, the political debate is already polarized but the aquaculture industry is so far getting the worst of it (Andenæs, 2012; Olsen & Osmundsen, 2017). However, we hope that we have shown that the question is multi-faceted and needs to be considered very carefully by the duly appointed committee.

9. Conclusion

In this thesis we have examined the potential knock-on effects on aquaculture and angling tourism, in regard to how global warming will affect the life-cycle of salmon lice. Intuitively one would expect the effects to be negative, which was borne out by our research. The only question here is one of degree. However, we view the breadth of the impact as somewhat surprising, spanning topics from the direct impact on fish-farms to real-estate prices along salmon rivers.

To elaborate both on the breadth and our results we began with the quantitative part of our thesis in chapters 4 and 5. There we went over the theory, datasets, and assumptions made for our simulation of how salmon lice infection pressure would be affected by climate change. For the most part the results were as expected: a steady trend of increasing infection pressure over time; but increasing distance from nearby aquaculture localities (firewalls) quickly diminished infection pressure. There were however some oddities, such as the “spikes” in section 5.10 (whose exact cause and potential consequences we cannot be certain of).

In the qualitative part of our assignment, chapter 6, we debated what effects the quantitative findings would have. There we found that not only would the increased infection pressure harm salmon aquaculture directly (by increased treatment cost, mortality, and downgrading of harvested salmon). It would also harm angling tourism, and thereby hurt local economies, cause loss of income to landowners, and potentially lead to decreased real-estate prices along salmon rivers.

We would also mention that global warming itself may in some cases improve salmon growth (Lorentzen & Hannesson, 2006), but, as we argue in section 6.3, Abolofia et al. (2017) show that this will not make up for the increased harm caused by the salmon lice.

By our definition of externality (see section 6.7.1) a relevant externality must cause the actors affected by it to attempt to limit it. We argue that this is exactly what we see, in that public discourse often trigger political and regulatory efforts to limit the threat of salmon lice. This has often been done in ways that are harmful to salmon aquaculture, especially when it comes to expansion efforts. Further we propose that this process is likely to continue in the future.

We do not go into the non-tangible value of the wild salmon. As we explain in section 7.5 this would necessarily run into Sami issues. Indeed, our literature search found that in-depth studies of the intangible value of the wild salmon seemed to focus on the Sami, with a few exceptions. We did not think ourselves capable of tackling this issue directly, nor did we think it would be ethical to pretend that it does not exist and speak simply of the intangible value to ethnic Norwegians.

The implications of our findings are detailed in chapter 8, and to recap:

1. Active awareness of global climate change.
   We need to take climate change and all of its consequences into account.
2. Looking for technological solutions.
   In section 8.2 we show that there are several promising avenues to go down, but it might raise costs and require extensive research and investment (Rosten et al., 2011; Shainee et al., 2013).
3. Firewalls.
   Although in the long-term firewalls limit the possible use of coastal areas, in the short term they are a proven way of protecting important and/or sensitive areas from salmon lice infection (Serra-Llinares et al., 2014).
4. Start preparing to relocate the industry northwards.
   The problem of salmon lice (and other pests) is always going to be reduced the further north you go. With increasing water temperatures the southern areas may also be increasingly unsuitable for aquaculture (Lorentzen & Hannesson, 2006).
5. Tax on economic rent.
   On one hand levying this tax and letting the proceeds go to local municipalities may seem like a suitable way of compensating these municipalities. However, doing so will make the industry less profitable which may hamper investments that are essential to get the salmon lice problem under control.

We would like to end by saying that that global warming will lead to a range of economic dislocations (Dietz et al., 2018; Fisher, Hanemann, Roberts, & Schlenker, 2012; Tol, 2018), in our thesis we have examined what appears to be one of many likely consequences.

Of course, we also have to state that all of our findings depend on the ROMS temperature data as well as the salmon lice infection pressure model that we used, and our proper understanding of both. In many places we have tried to interpret models and papers that are far outside of our own field, however multidisciplinary industrial economics is, and we cannot be certain that we have not misinterpreted or misapplied some of this data. Although we have done our best to contact experts when we were in doubt, we might again have misunderstood or misapplied what they told us. Such mistakes are entirely ours.

We would also like to point out that we only had a single temperature dataset, which limited our study. If in the future it would be possible to have multiple datasets, that is a larger sample, we could have more meaningful statistical analysis. Given the importance of such projections we hope that this will be an area where future effort and investments will be made.

Further we would state that we have indeed only scratched the surface, due to the sheer breadth of the topic. The topic requires extensive further studies, to which our thesis can only be a small guideline, whether an example to emulation or a warning of what not to do.

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